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Transverse Impact on S-2 Glass Yarns: Analysis of Crimp and Other Effects on the Critical and Transverse Wave Velocities

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SwRI®

Outline

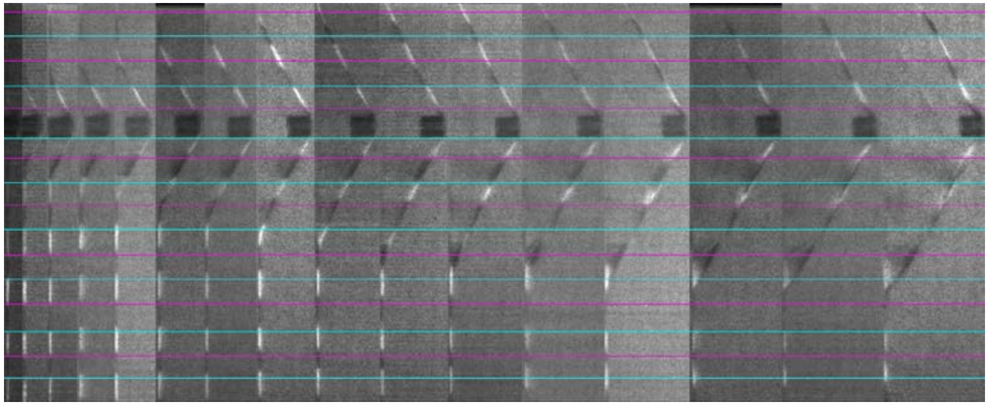
- Background: Tests on Kevlar®, PBO®, and Dyneema®
- Tests on S-2 glass
- Continuum Mechanics Approach
- Simulations with LS-DYNA
- Discussion
- Conclusions

Single Yarn Impact Validation

Smith theory on transverse impact on single yarns

$$V = c\sqrt{\varepsilon\left(2\sqrt{\varepsilon(1+\varepsilon)}-\varepsilon\right)}$$

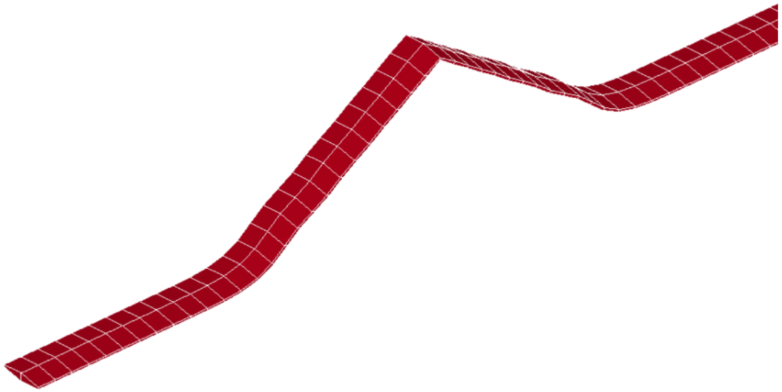
$$U = c\left(\sqrt{\varepsilon(1+\varepsilon)}-\varepsilon\right)$$



Yarn Material	Density (g/cc)	Sound Speed (km/s)	Strength (GPa)	Theor. Critical Velocity (m/s)
KM2 S5705	1.44	7.45	3.4	945
Dyneema SK-65	0.97	9.89	3.42	1110
PBO	1.56	10.7	5.8	1108

Single Yarn Impact Validation

Transverse Wave Velocity in polymeric fibers is very well captured by the finite element code.



Yarn Material	Impact vel. (m/s)	Theor.Transv. wave vel. (m/s)	Exp. Transv. wave vel. (m/s)	LS-DYNA Transv. wave vel. (m/s)
KM2 S5705	480	851	880	880
Dyneema SK-65	480	954	900	950
PBO	520	1033	1040	1060

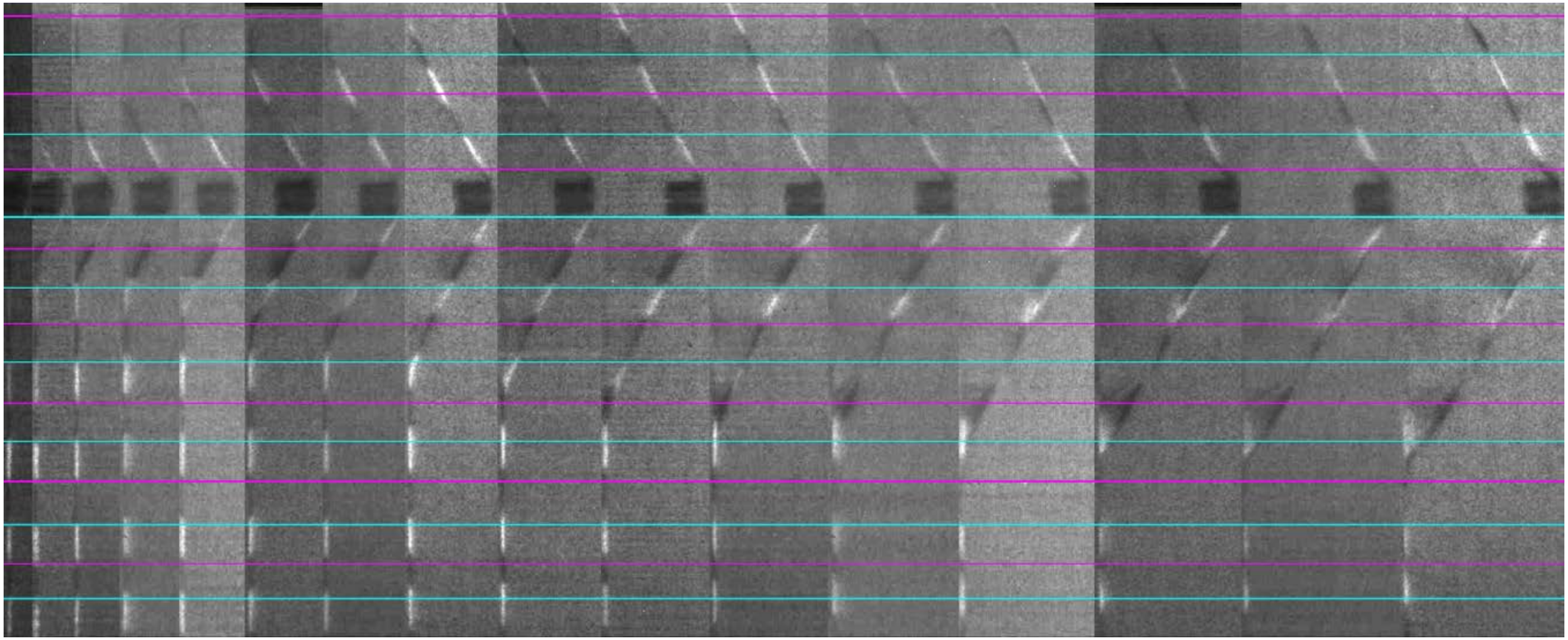
Material	Density (g/cm^3)	E_a (GPa)	E_b (GPa)	E_c (GPa)	ν	G (GPa)	σ_u (GPa)
KM2 S5705	1.44	80	8.0	8.0	0	0.8	3.4
Dyneema SK-65	0.97	95	9.5	9.5	0	0.95	3.42
PBO	1.56	180	18	18	0	1.8	5.8

Critical Velocity for Yarns

Yarn	Exp. Critical Vel. (m/s)	LS-DYNA Crit. Vel. (m/s)	Crit. Vel. Smith (m/s)	Crit. Vel. Walker (m/s)
KM2 S5705	621-634	557	934	565
Dyneema SK-65	517-583	672	1100	664
PBO	523-610	692	1105	666

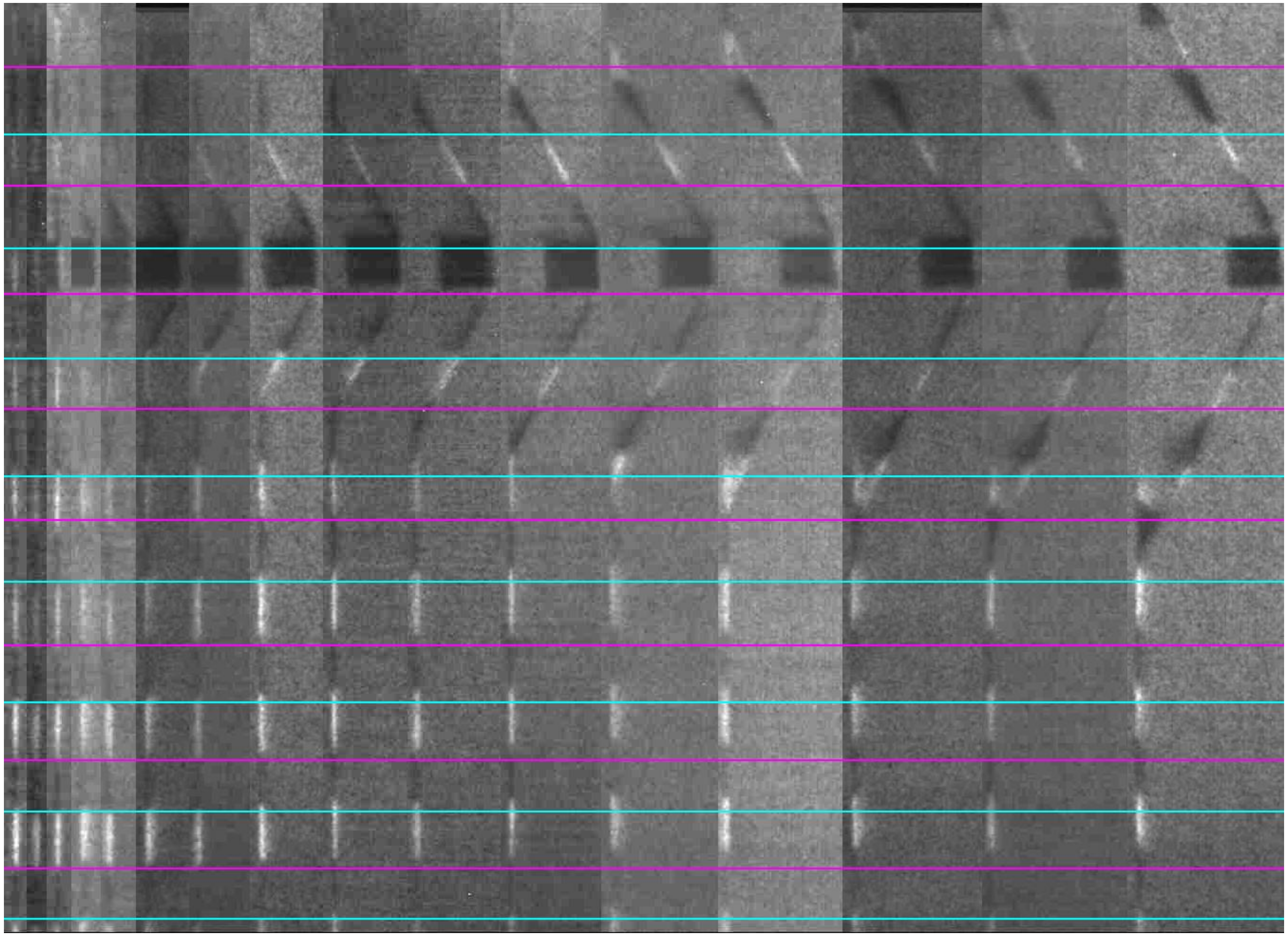
Clearly the numerical model is a simplification for yarn impact. It captures very well the transverse wave velocity but more work needs to be done on the critical velocity.

Yarn 03 – Dyneema SK65 – 477m/s
5 us per frame



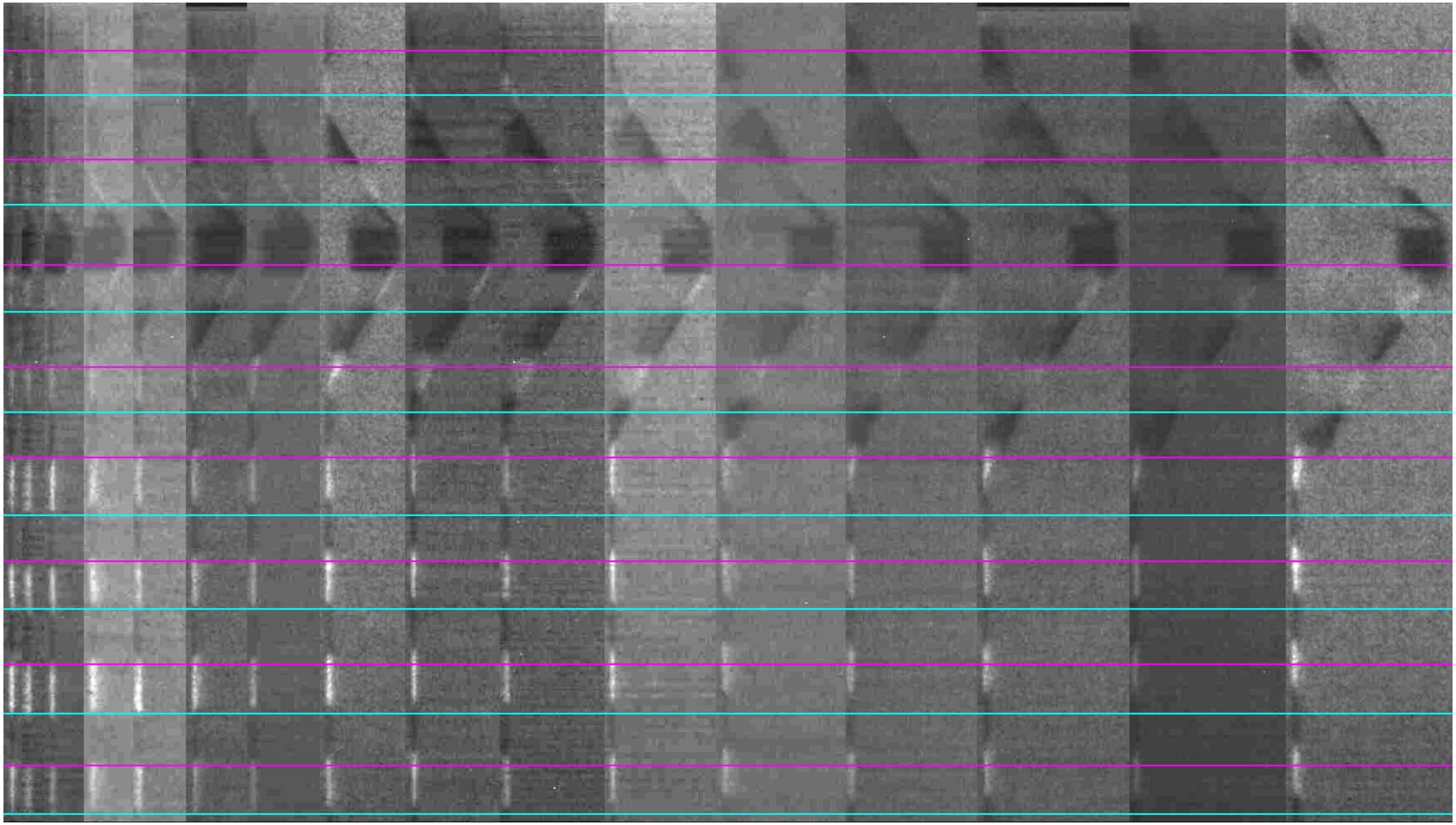
No failure

Yarn 06 – Dyneema – 474m/s
4 us per frame



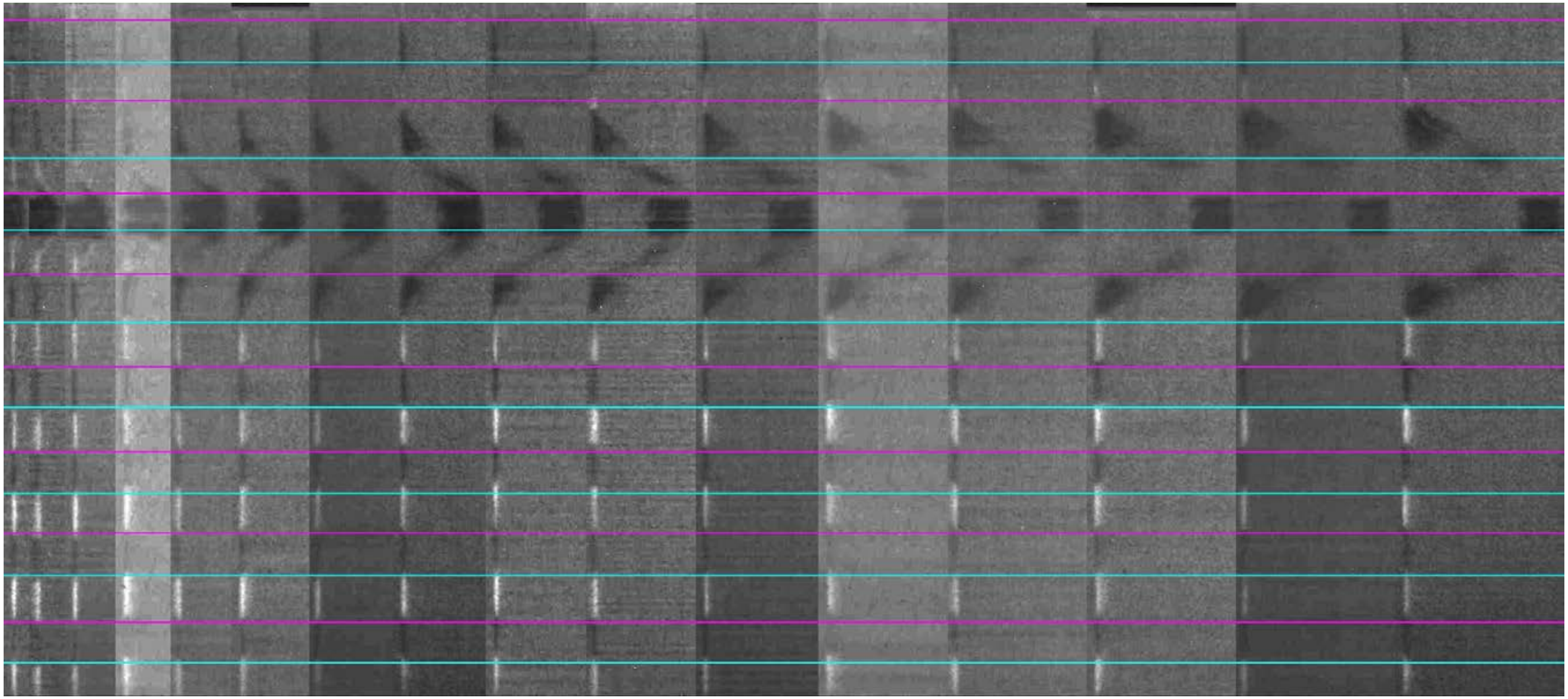
No failure

Yarn 12 – Dyneema – 517m/s
4 us per frame



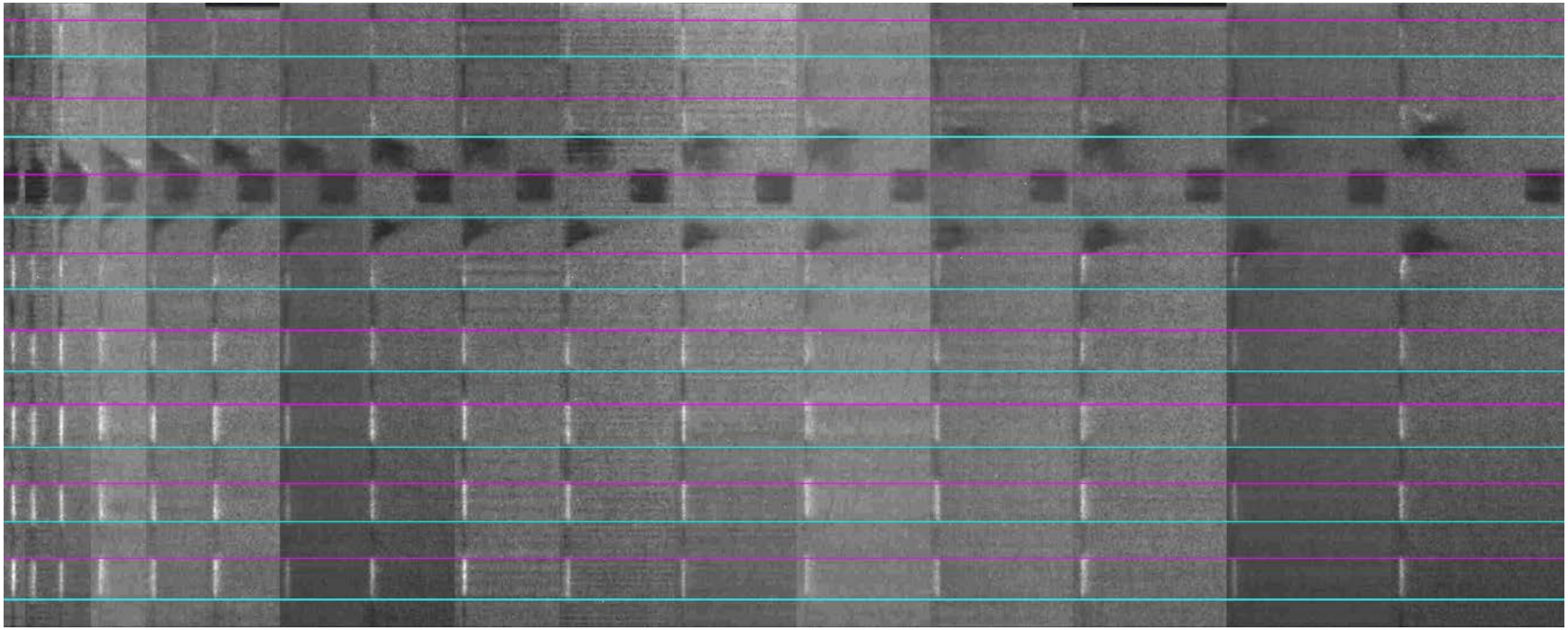
No failure

Yarn 11 – Dyneema – 583m/s
4 us per frame



Immediate failure

Yarn 09 – Dyneema – 672m/s
4 us per frame

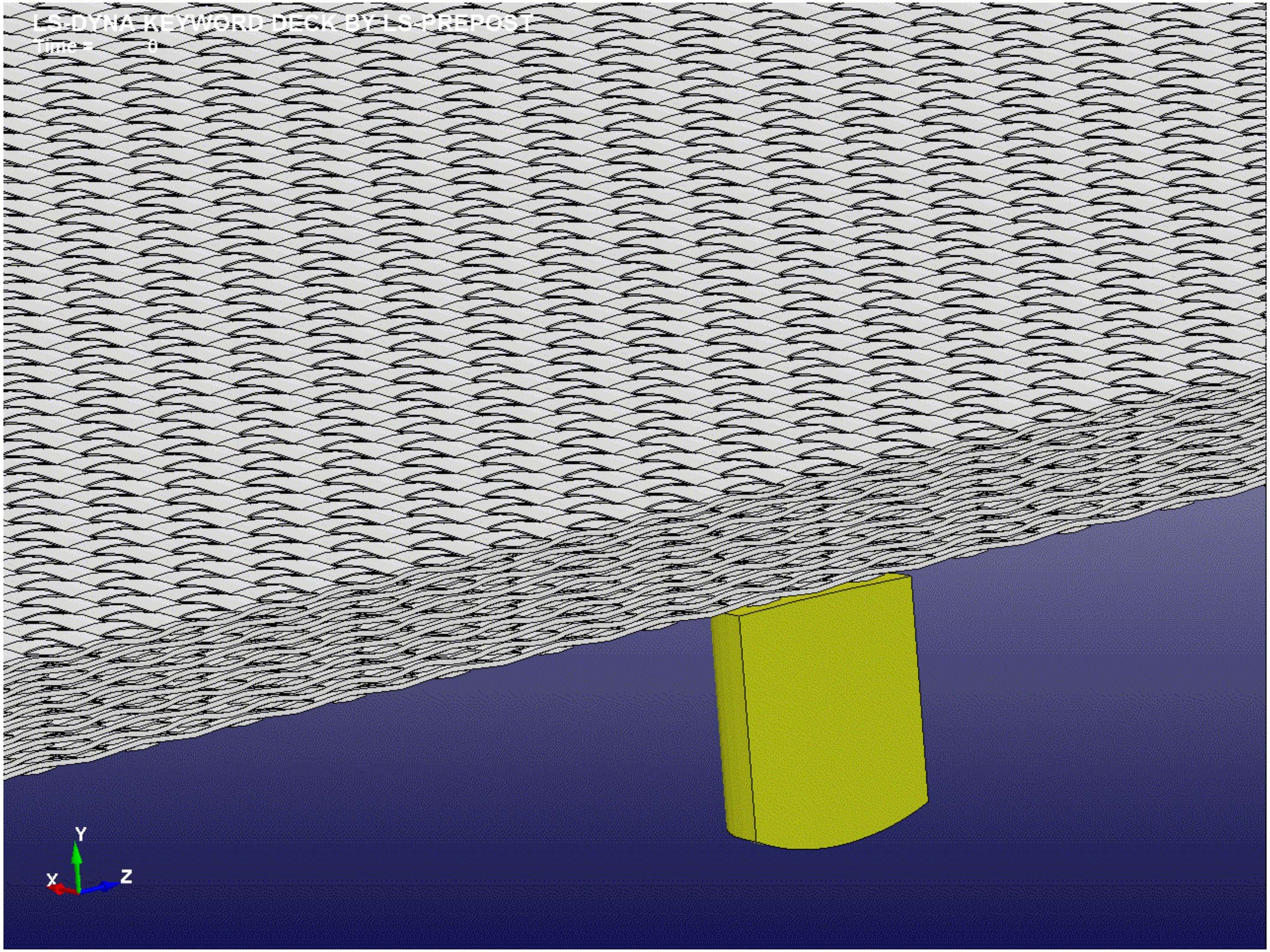


Immediate failure

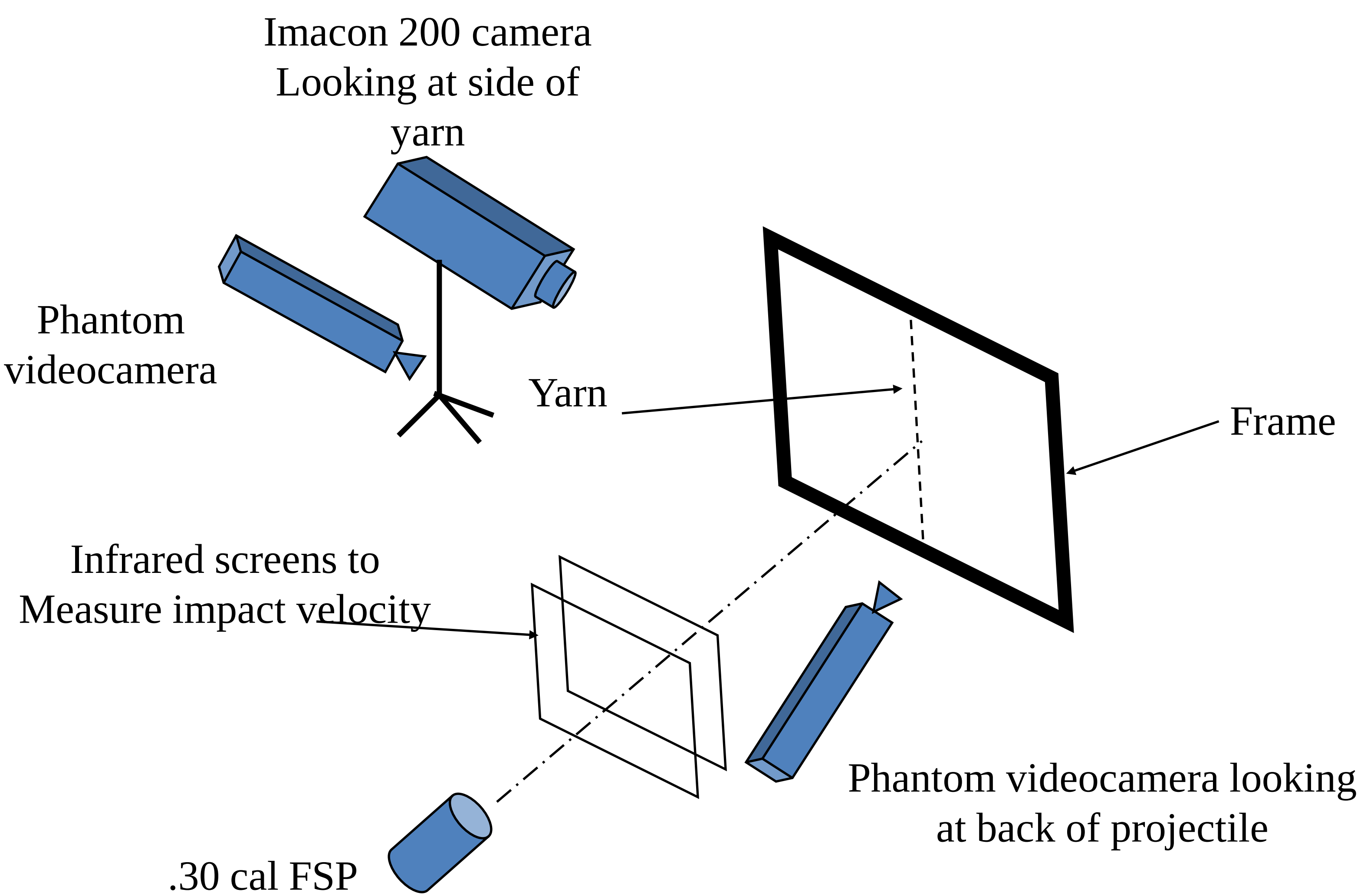
Why is it important to understand impact on single yarns?

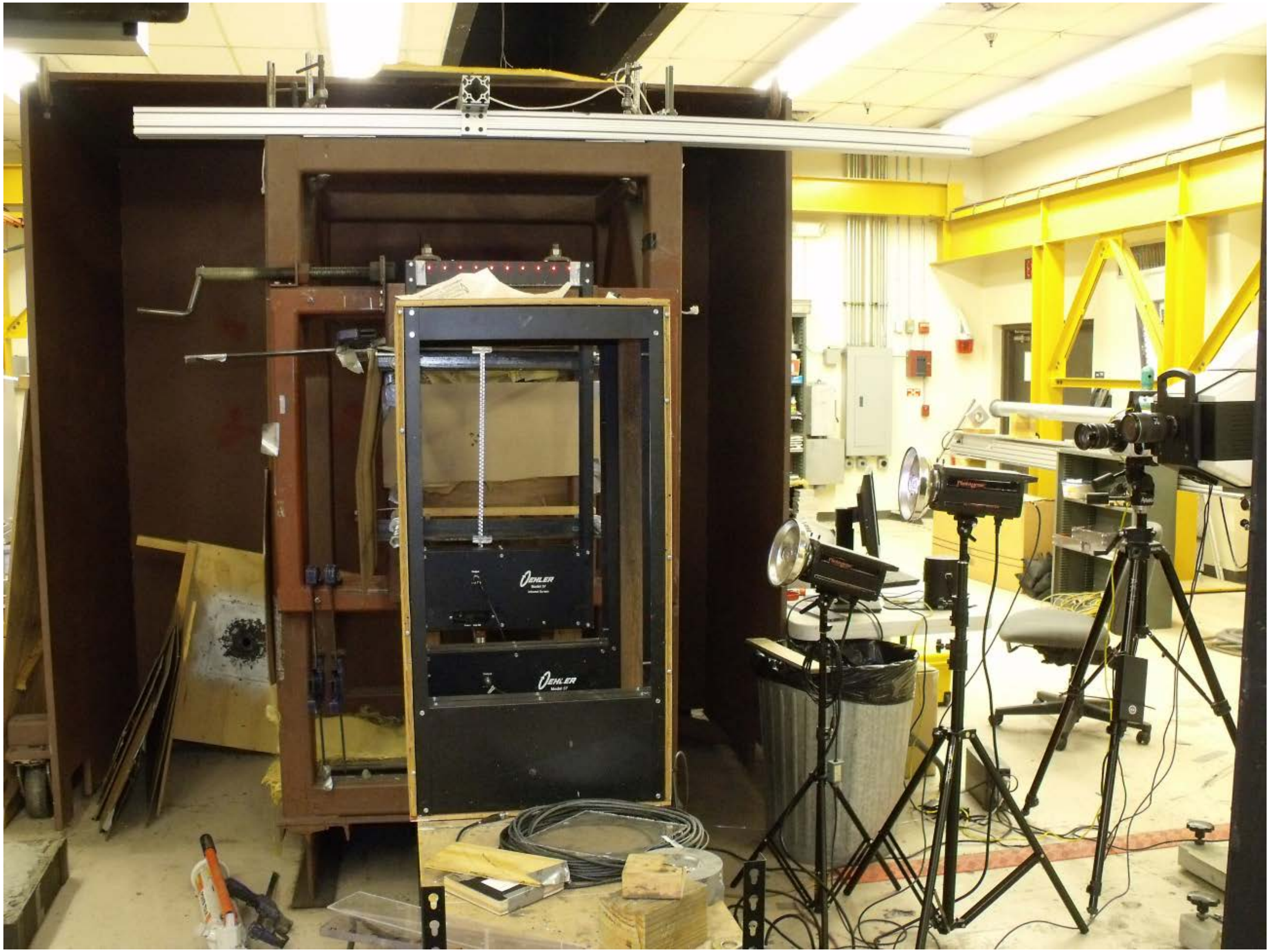
- Elastic properties of yarns are validated by matching the transverse wave velocity.
- Failure properties of yarns are validated by (hopefully) matching the critical velocity.
- If both are properly predicted and understood then we should be able to put yarns together and create a fabric or composite "mesoscale" model that predicts deflection and ballistic limit.
- This has actually been done with Kevlar and partially with Dyneema with very good results.
- Work is in progress to obtain an S-2 glass composite mesoscale model.

Impact on Dyneema Fabric



Test set-up for S-2 Glass Yarns

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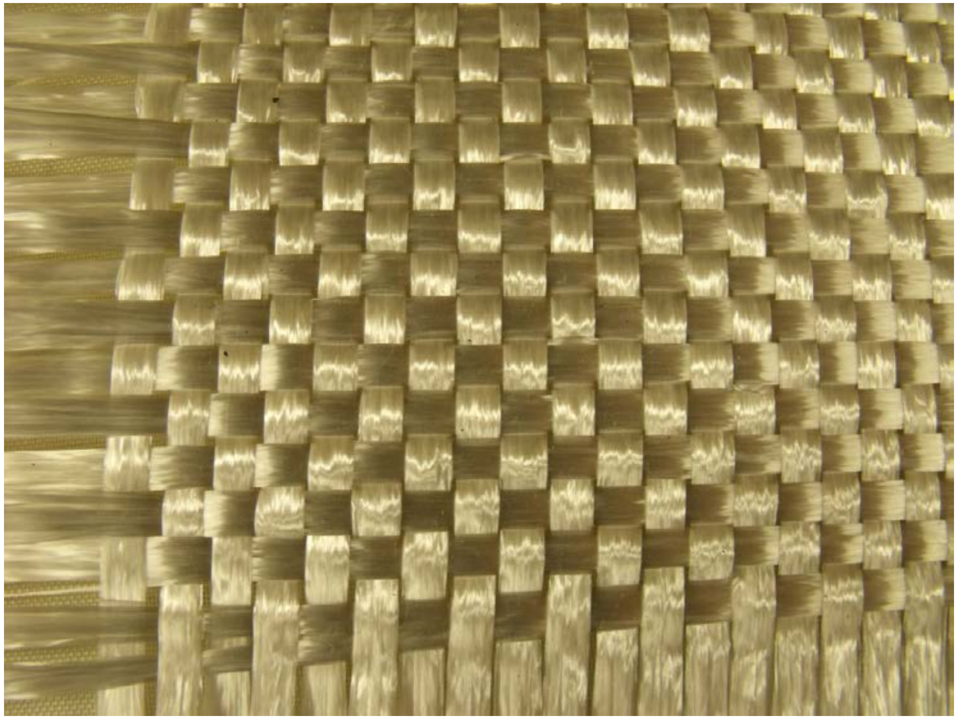
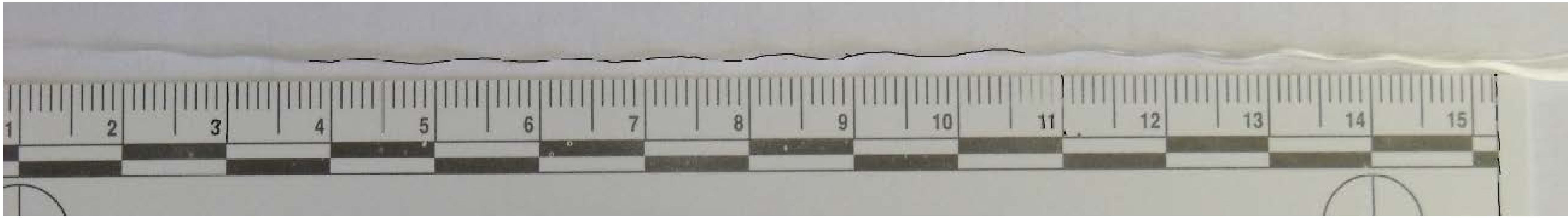
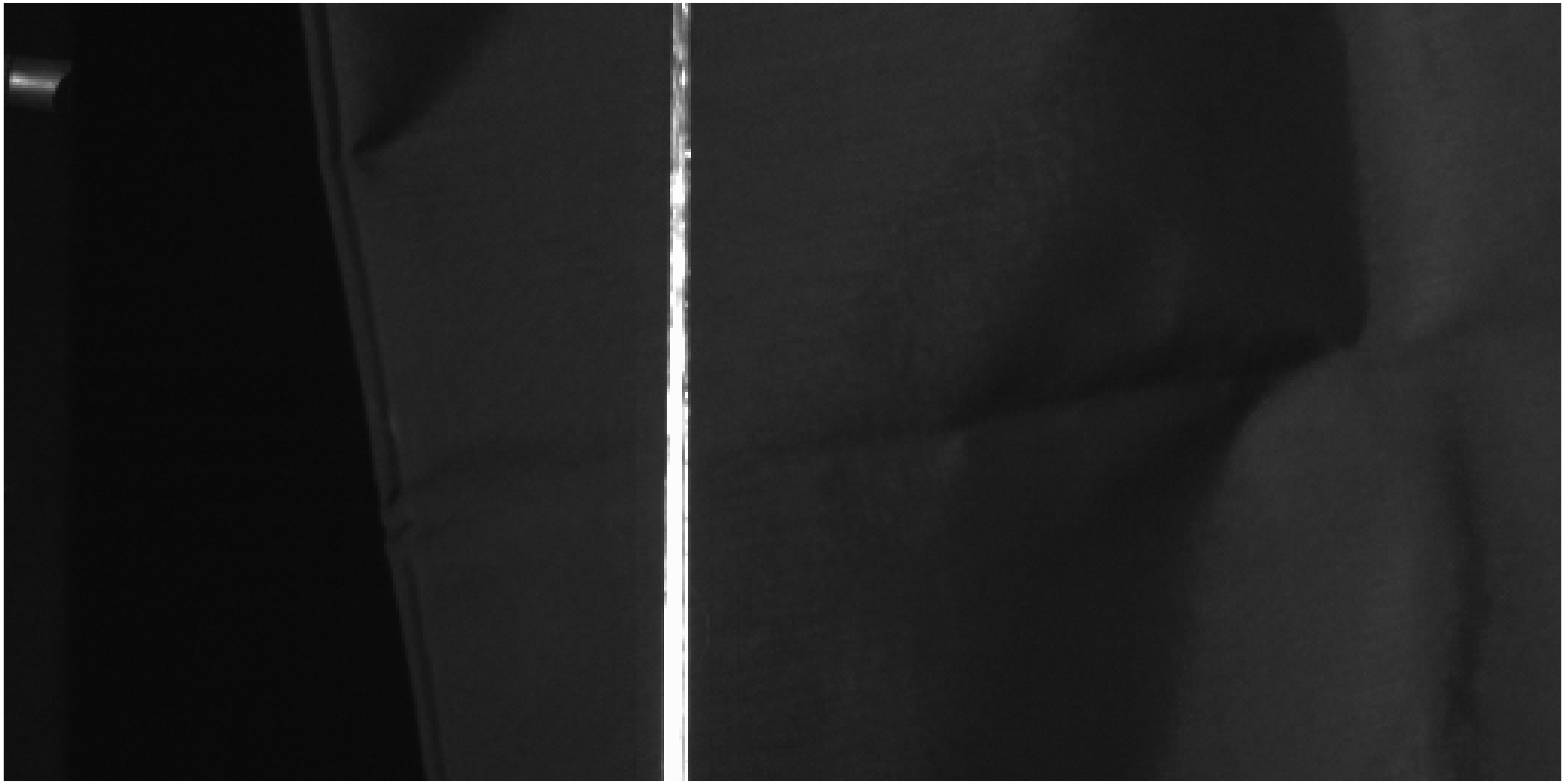
OEHLER

S-2 Glass Yarn and Crimp



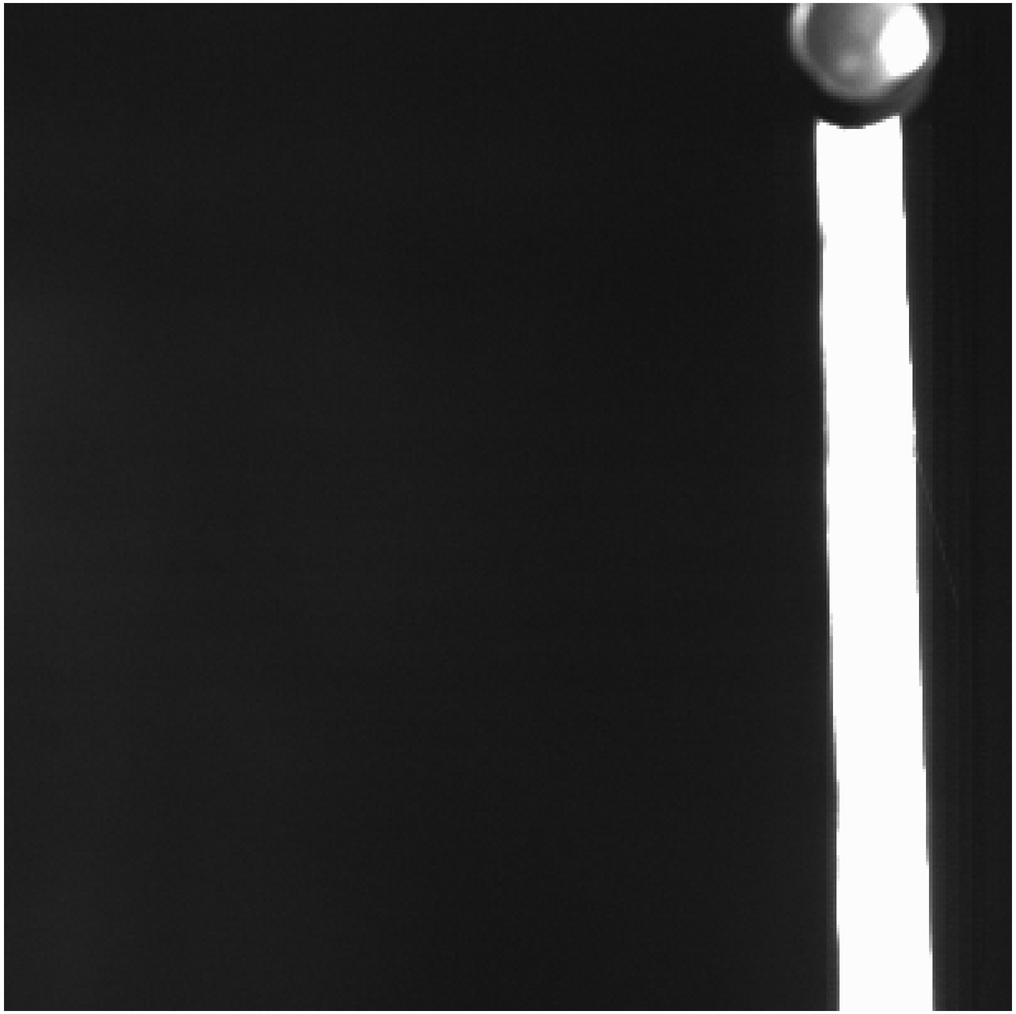


S2-Glass – Test 26 – 183 m/s
Side View – Below Critical Velocity



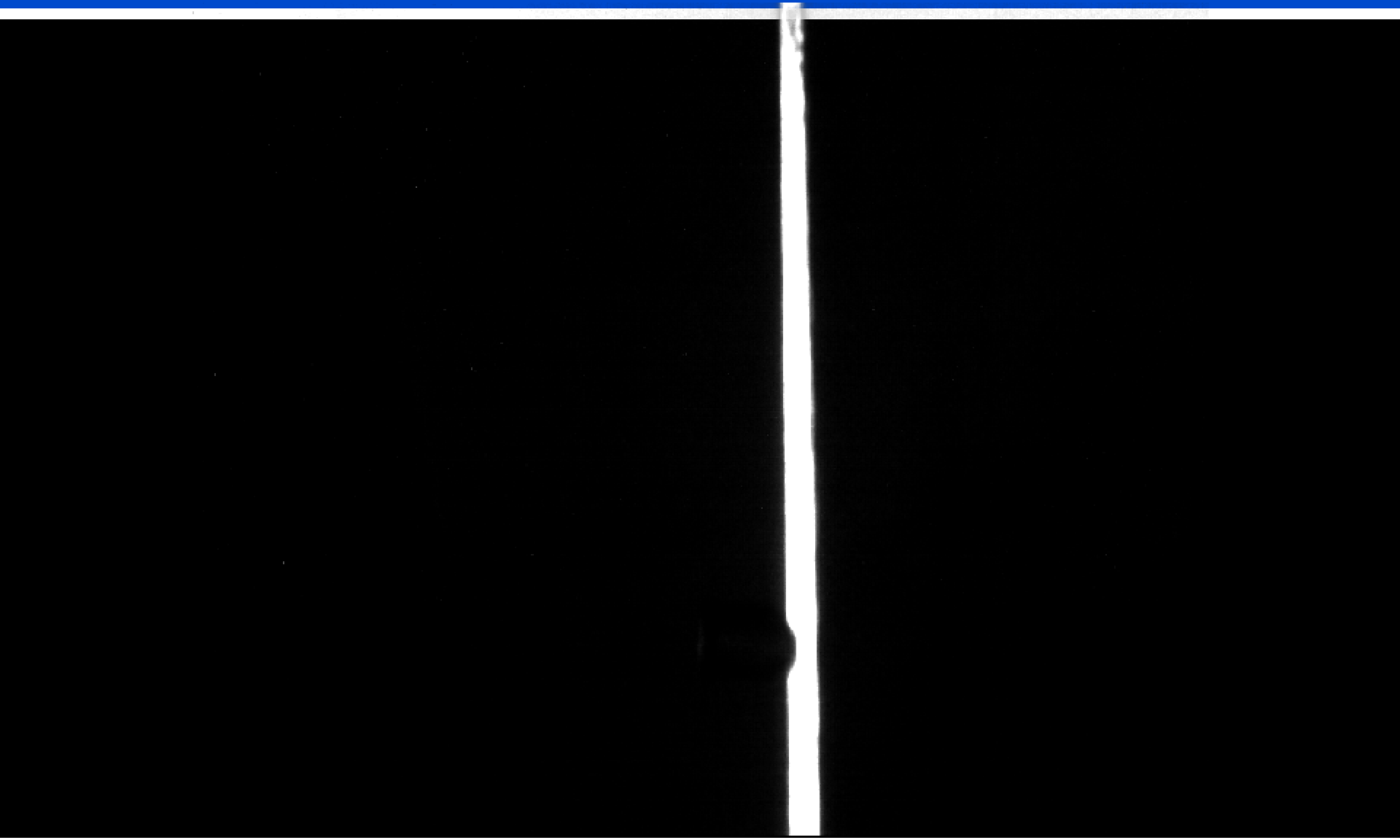
Phantom Camera: one image every 20.4 μs.

S2-Glass – Test 26 – 183 m/s
Front View – Below Critical Velocity



Phantom Camera: one image every 20.4 μs.

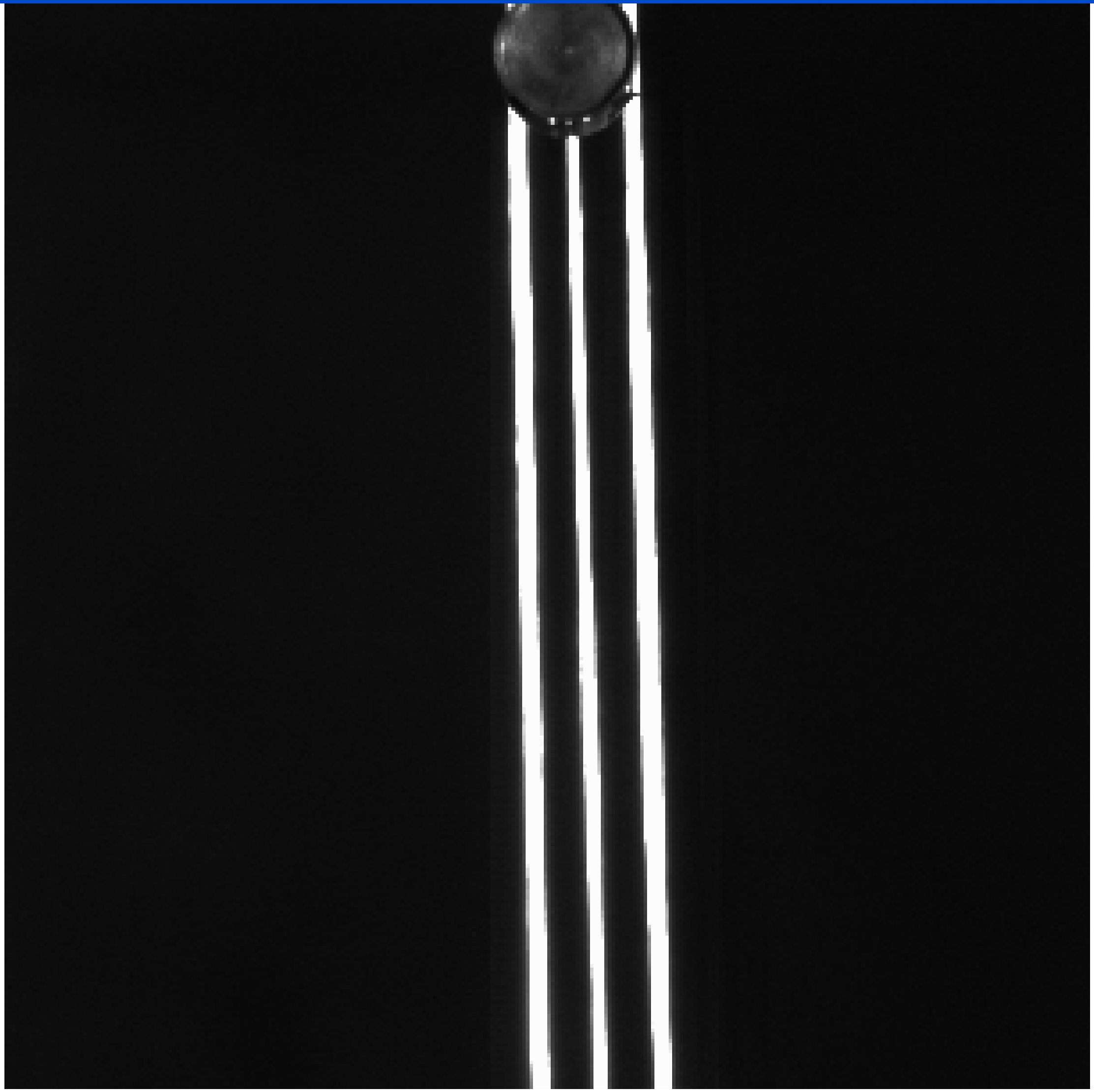
S2-Glass – Test 26 – 183 m/s
Imacon, one frame every 5 μs



S2-Glass – Test 39 – 400 m/s
Side View – Above Critical Velocity

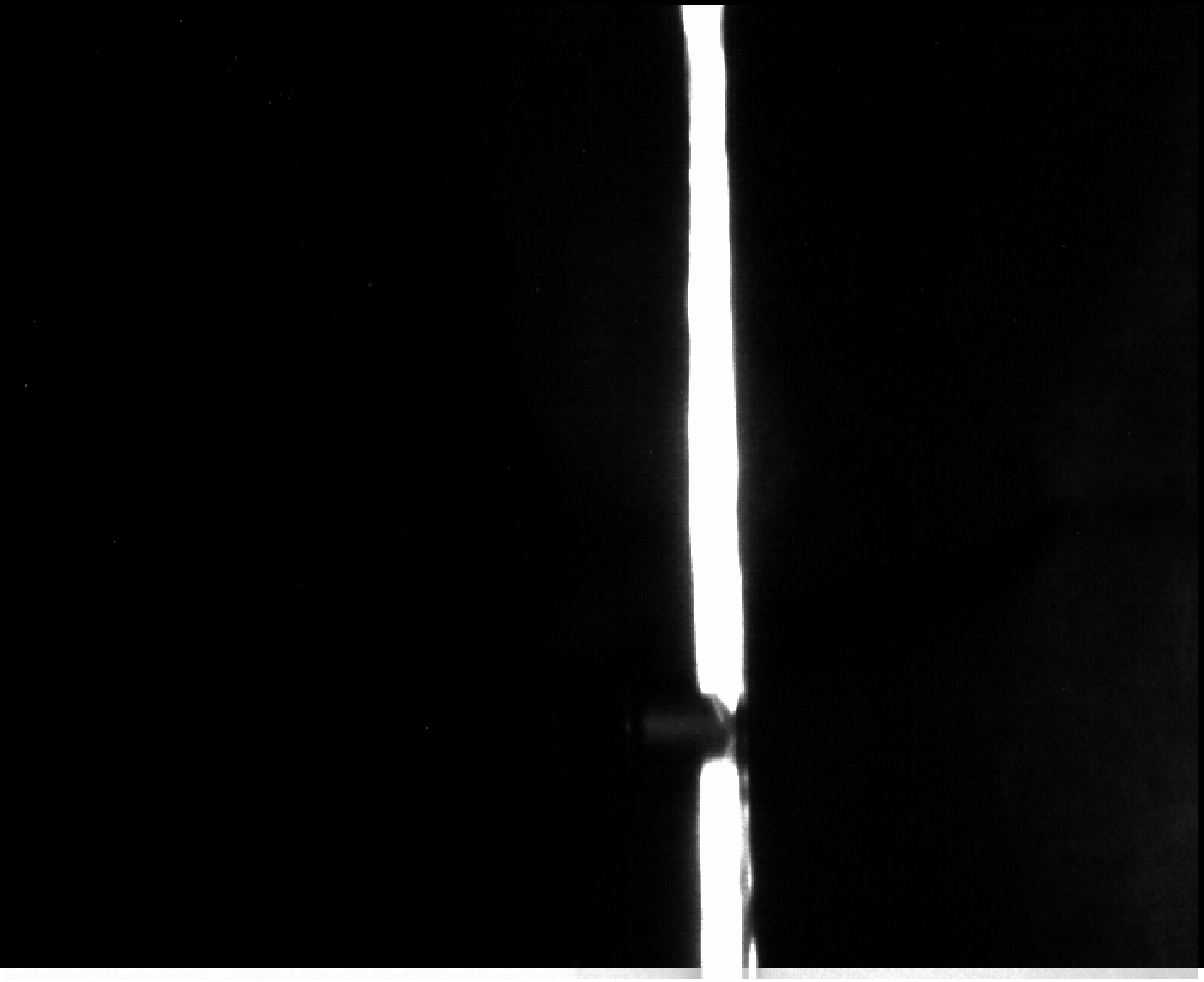
Phantom Camera: one image every 20.4 μs.

S2-Glass – Test 39 – 400 m/s
Front View – Above Critical Velocity

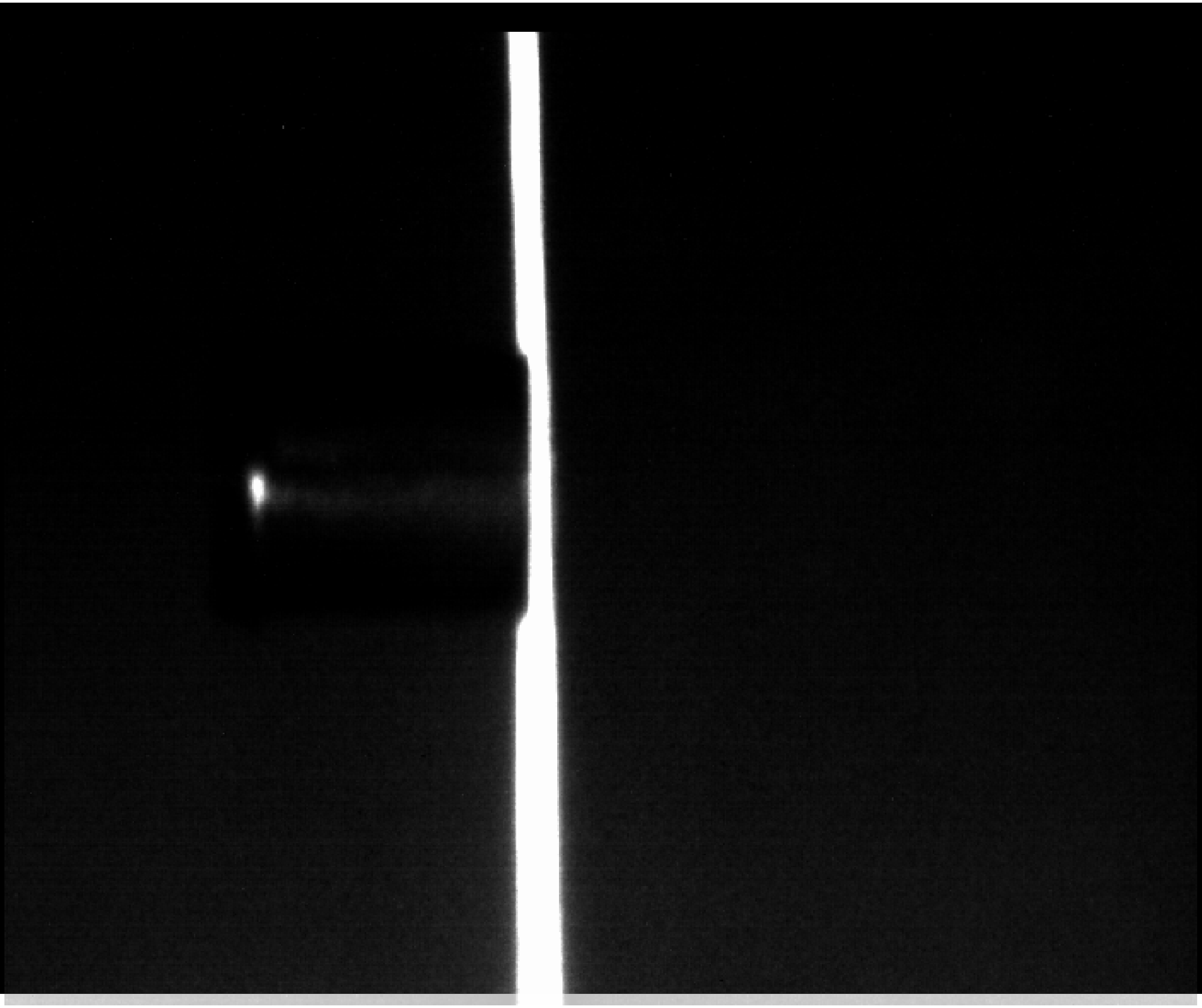


Phantom Camera: one image every 20.4 μs.

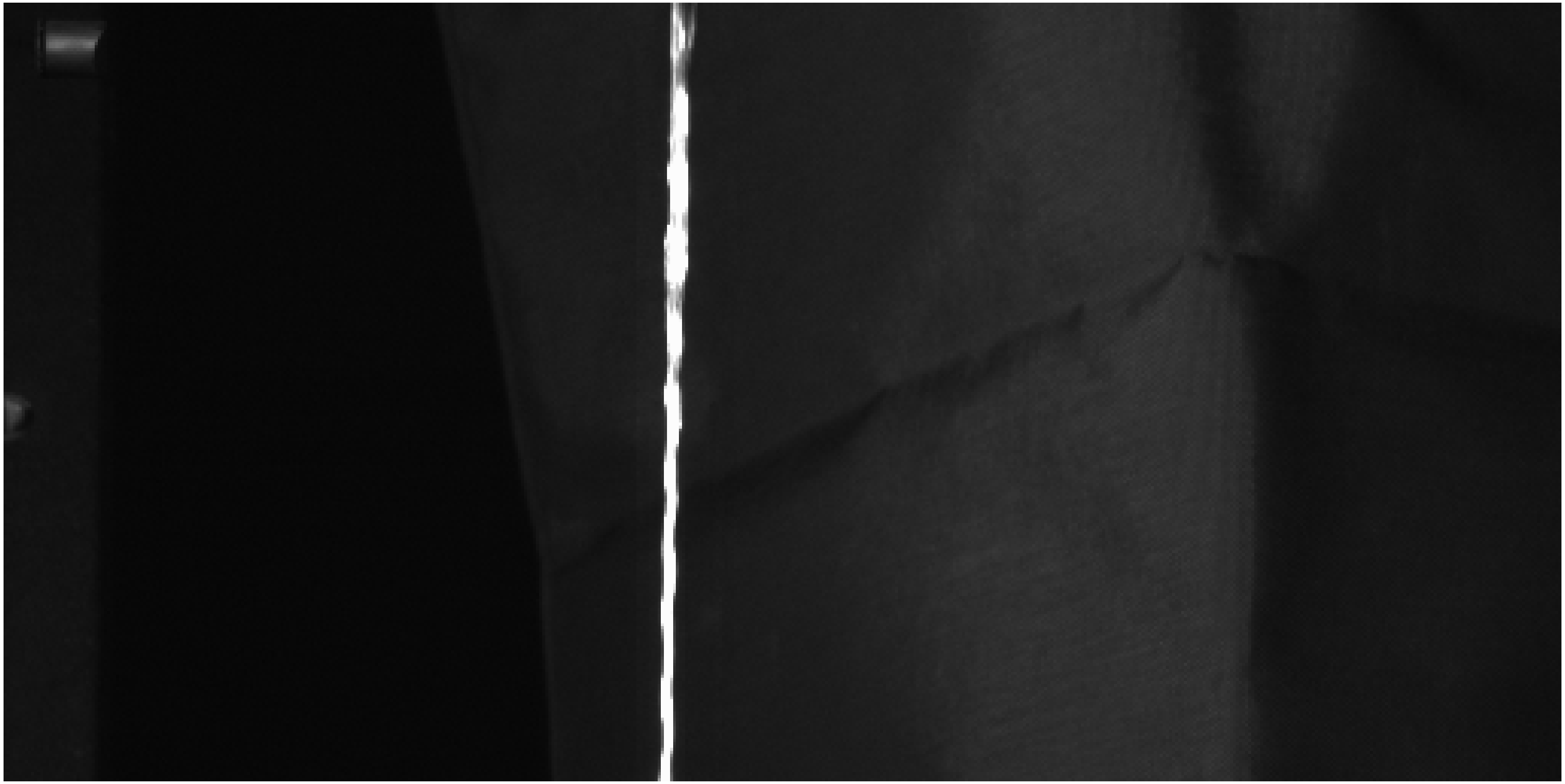
S2-Glass – Test 21 – 408 m/s
Imacon, one frame every 5 μs



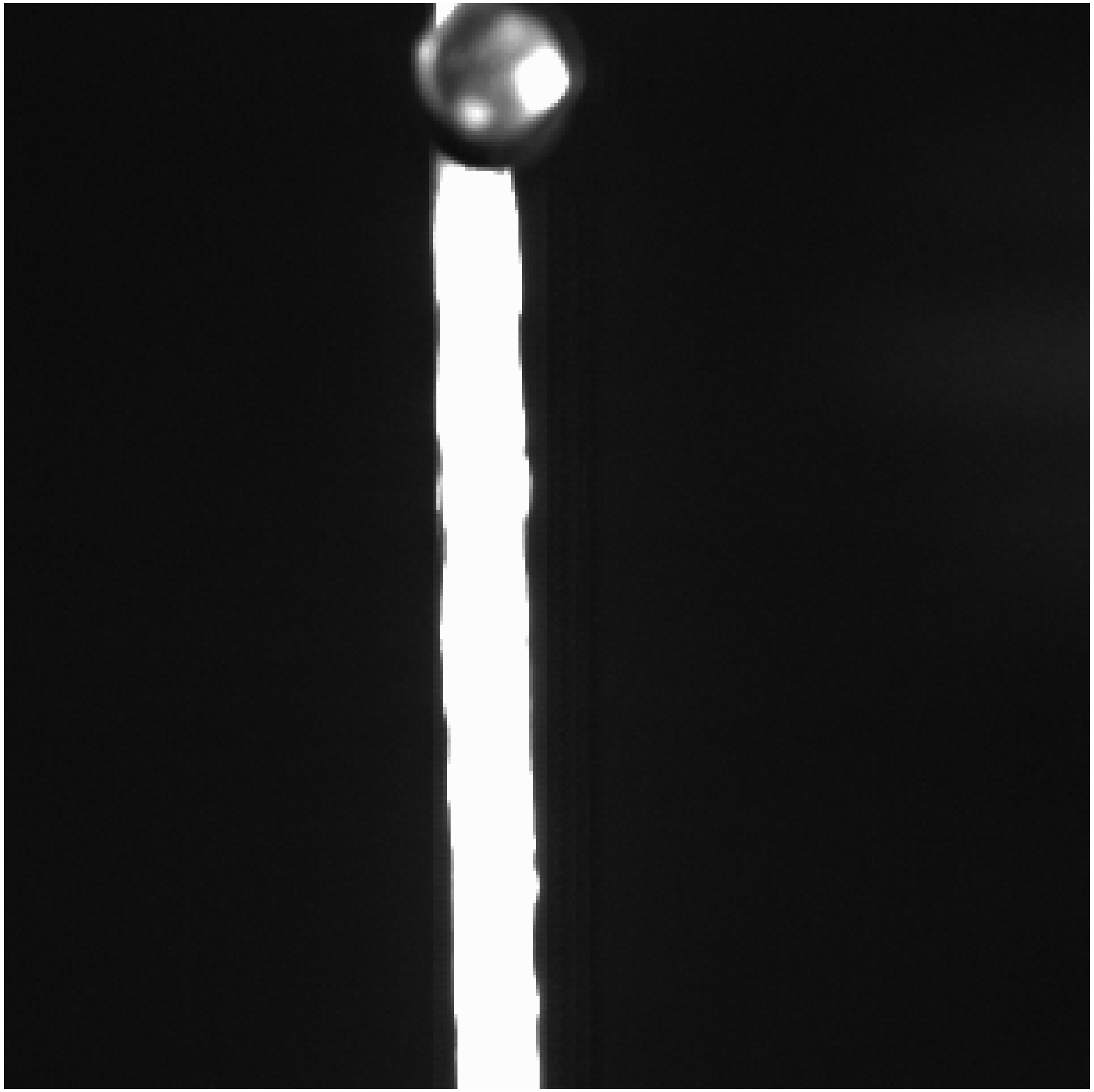
S2-Glass – Test 39 – 400 m/s
Imacon, one frame every 0.5 μs



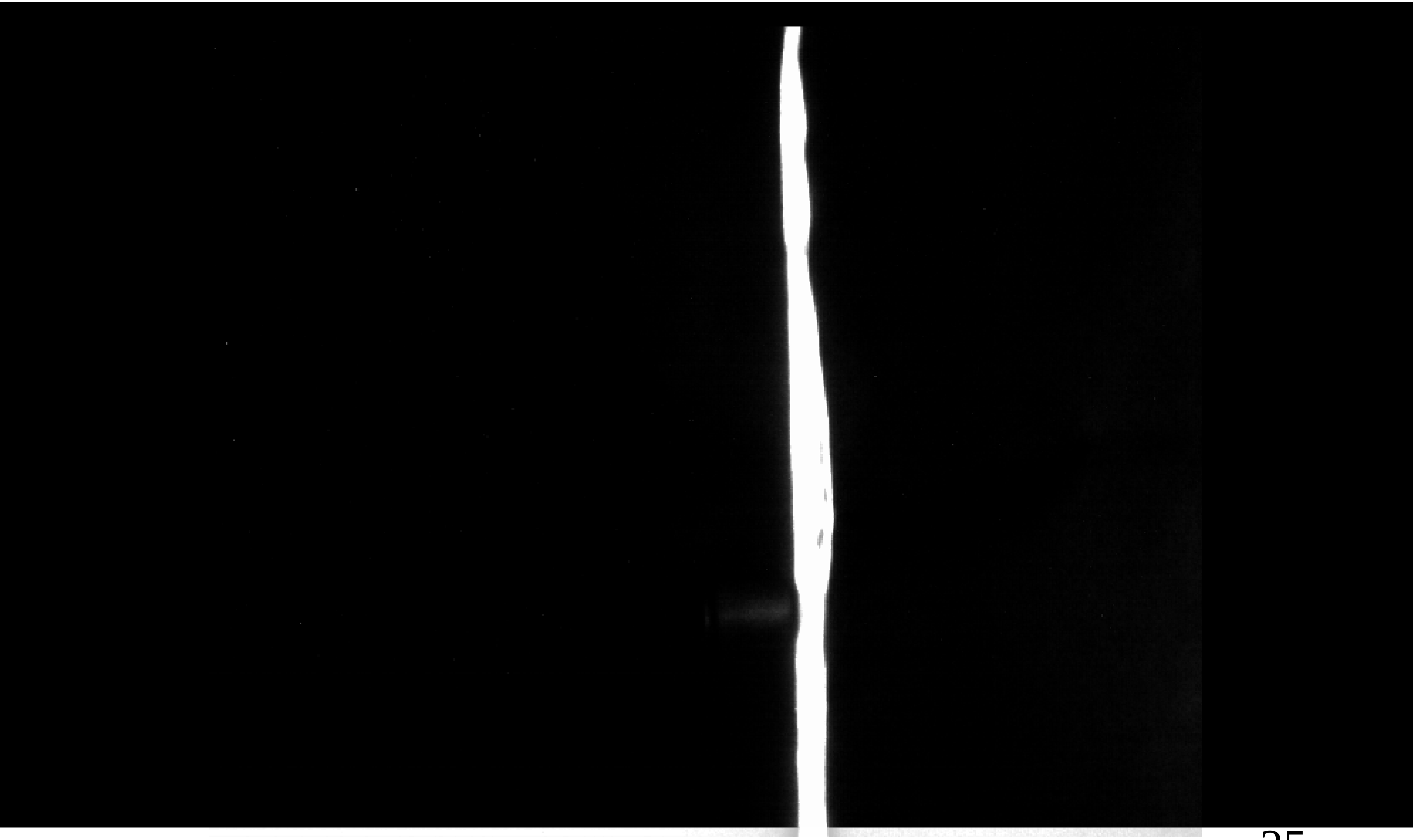
S2-Glass – Test 11 – 279 m/s
Side View – Transition Velocity



S2-Glass – Test 11 – 279 m/s
Front View – Transition Velocity



S2-Glass – Test 11 – 274 m/s
Imacon, one frame every 5 μs

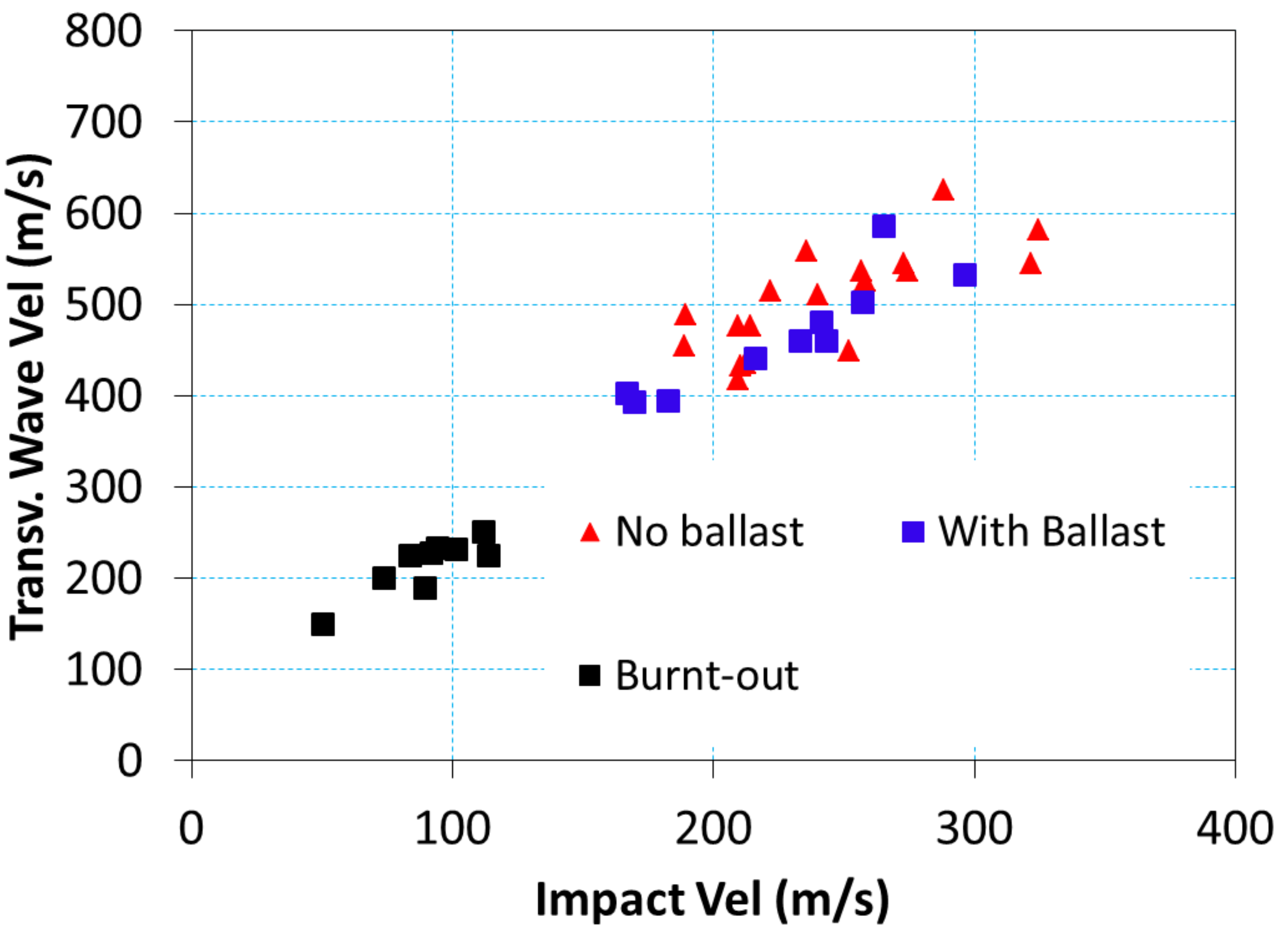


Results on S-2 Glass

Test ID	Speed (ft/s)	Speed (m/s)	V_c	Trans. Wave Vel. (m/s)	Smith Wave Vel. (m/s)	Walker Wave Vel (m/s)	Smith Strain (%)	Walker Strain (%)
T27	547	167	B	402	405.7	359.2	0.57	0.86
T28	556	170	B	393	410.0	363.7	0.58	0.88
T26	600	183	B	394	429.6	384.7	0.64	0.94
T16	620	189	B	454	438.6	394.2	0.67	0.97
T19	621	189	B	488	438.8	394.4	0.67	0.97
T17	686	209	B	477	466.9	424.3	0.77	1.06
T18	686	209	B	417	467.0	424.4	0.77	1.06
T20	690	210	B	433	468.4	425.8	0.77	1.07
T15	697	212	B	435	471.4	428.9	0.79	1.08
T14	703	214	B	476	473.7	431.4	0.79	1.09
T1	707	216	B		475.7	433.5	0.80	1.09
T31	709	216	B	441	476.3	434.2	0.80	1.10
T3	728	222	B	514	484.2	442.5	0.83	1.13
T25	766	233	AB	460	499.4	458.5	0.89	1.18
T4	774	236	B	559	502.6	461.9	0.90	1.20
T2	787	240	B	511	508.0	467.5	0.93	1.22
T24	792	241	AB	480	509.7	469.3	0.93	1.22
T23	798	243	B	460	512.3	472.0	0.94	1.24
T5	827	252	AB	449	523.4	483.6	0.99	1.28
T10	842	257	AB	537	529.3	489.8	1.01	1.31
T30	843	257	AB	503	529.5	490.0	1.02	1.31
T13	847	258	B	525	531.1	491.7	1.02	1.31
T29	871	265	AB	586	540.1	501.1	1.06	1.35
T6	895	273	AB	545	549.2	510.5	1.10	1.39
T11	899	274	AB	537	550.8	512.2	1.11	1.40
T12	945	288	AB	625	567.7	529.8	1.19	1.48
T22	972	296	AB	533	577.4	539.8	1.23	1.52
T8	1055	322	AB	545	606.5	569.8	1.38	1.67
T9	1064	324	AB	581	609.4	572.8	1.39	1.68
T7	1160	354	A		641.8	606.0	1.57	1.86
T21	1338	408	A		698.1	663.3	1.90	2.20

- The critical velocity is somewhere between 222 and 354 m/s.
- Large transition zone.
- We will see that the scatter is very large for transverse wave velocities.

Results on S-2 Glass



- Without ballast the scatter is very large.
- Ballast was small: 800 g.
- Burnt out yarns have a critical velocity much smaller: 110 m/s.

Some Continuum Mechanics

Analytical Solution with Crimp

- Smith's simple solution does not take into account crimp on the yarn.
- Both Smith and Walker assume that **the only strain happening is in the longitudinal direction of the yarn**.
- There is **no shear strain or bending stiffness in both approaches**.
- Walker starts by writing the elastic energy per unit of volume in the yarn:

$$e = \frac{1}{2} E E_{11}^2$$

- A yarn with crimp E_0<0 has a smaller energy: $$e = \frac{1}{2} E (E_{11} + E_0)^2$$
- Using the fact that the first Piola-Kirchhoff stress tensor and the transpose of the deformation gradient are conjugate it is possible, in the Lagrangian frame, to obtain the relation between stress and strains.
- The relation is then used in the jump conditions across the longitudinal and transverse waves.

Analytical Solution with Crimp

- Jump conditions across longitudinal and transverse wave:

$$-E(E_{11L}+E_0)F_{11L}+T_0=\mathrm{c}_1\rho_0 v_{xL}$$

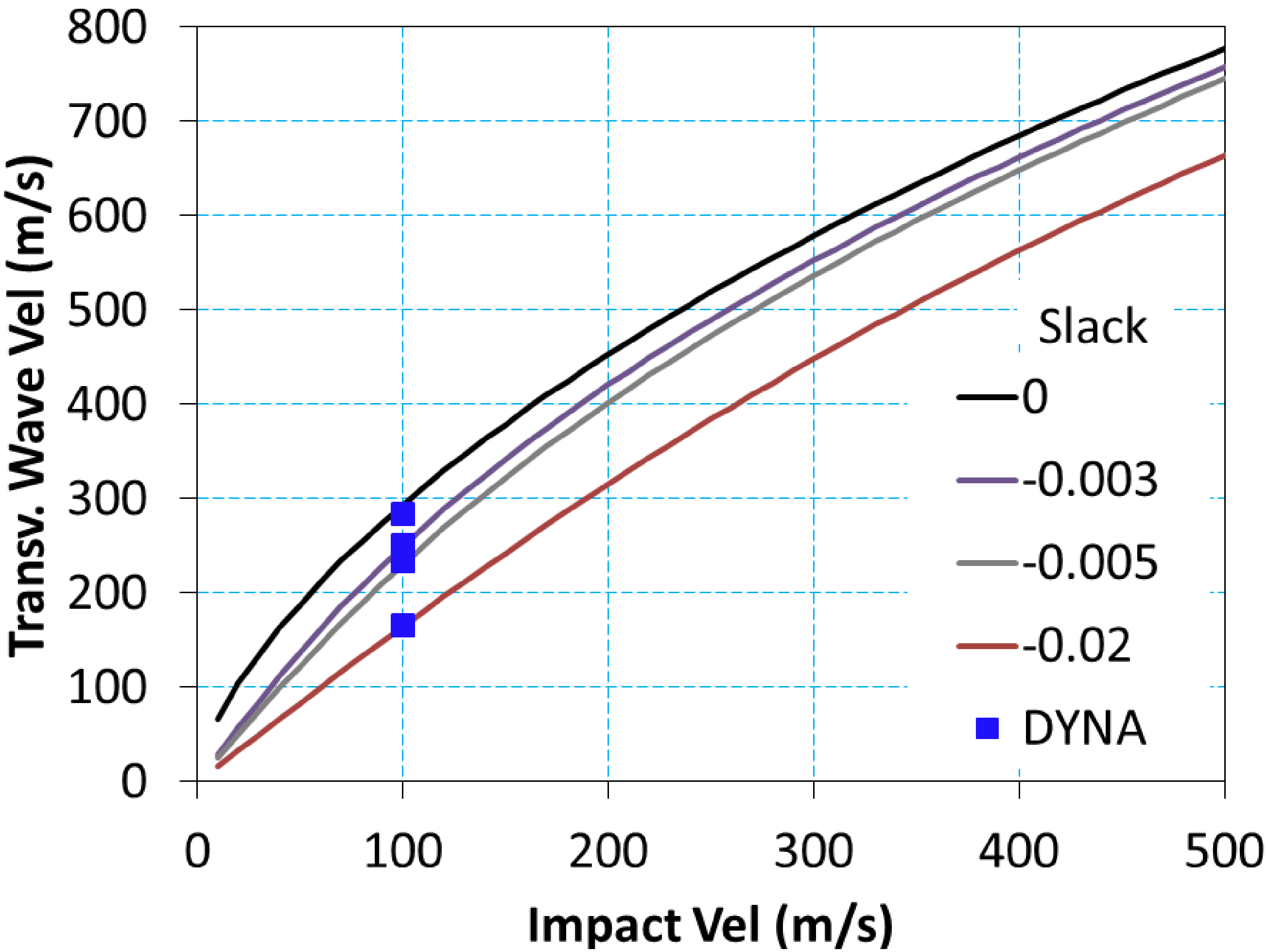
$$-E(E_{11T}+E_0)F_{11T}+E(E_{11L}+E_0)F_{11L}=\mathrm{c}_2\rho_0(v_{xT}-v_{xL})$$

$$-E(E_{11T}+E_0)F_{31T}=\mathrm{c}_2\rho_0 v_z$$

- They can be solved to find the longitudinal wave speed, transverse wave speed, and particle velocity in yarn. The transverse wave speed in the laboratory frame is:

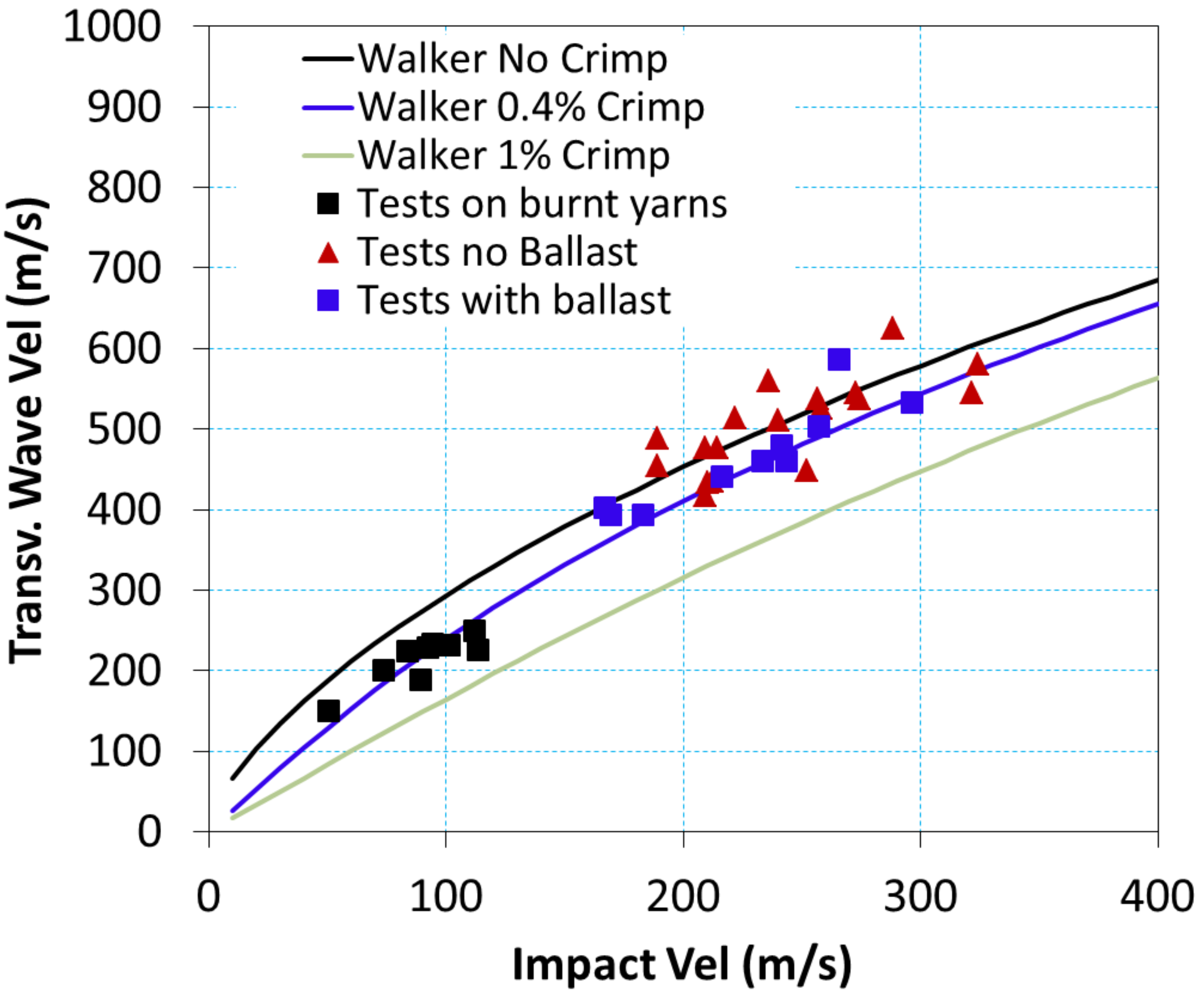
$$\frac{U_T}{c_E}=\frac{c_2}{c_E}+\frac{v_{xL}}{c_1}\frac{c_1}{c_E}\left(1-\frac{c_2}{c_1}\right)\cong\sqrt{E_{11}+E_0}\left(1-\sqrt{E_{11}}\right)$$

Checking the Analytical Solution



- Also note that with zero crimp the solutions from Walker and Smith are almost identical

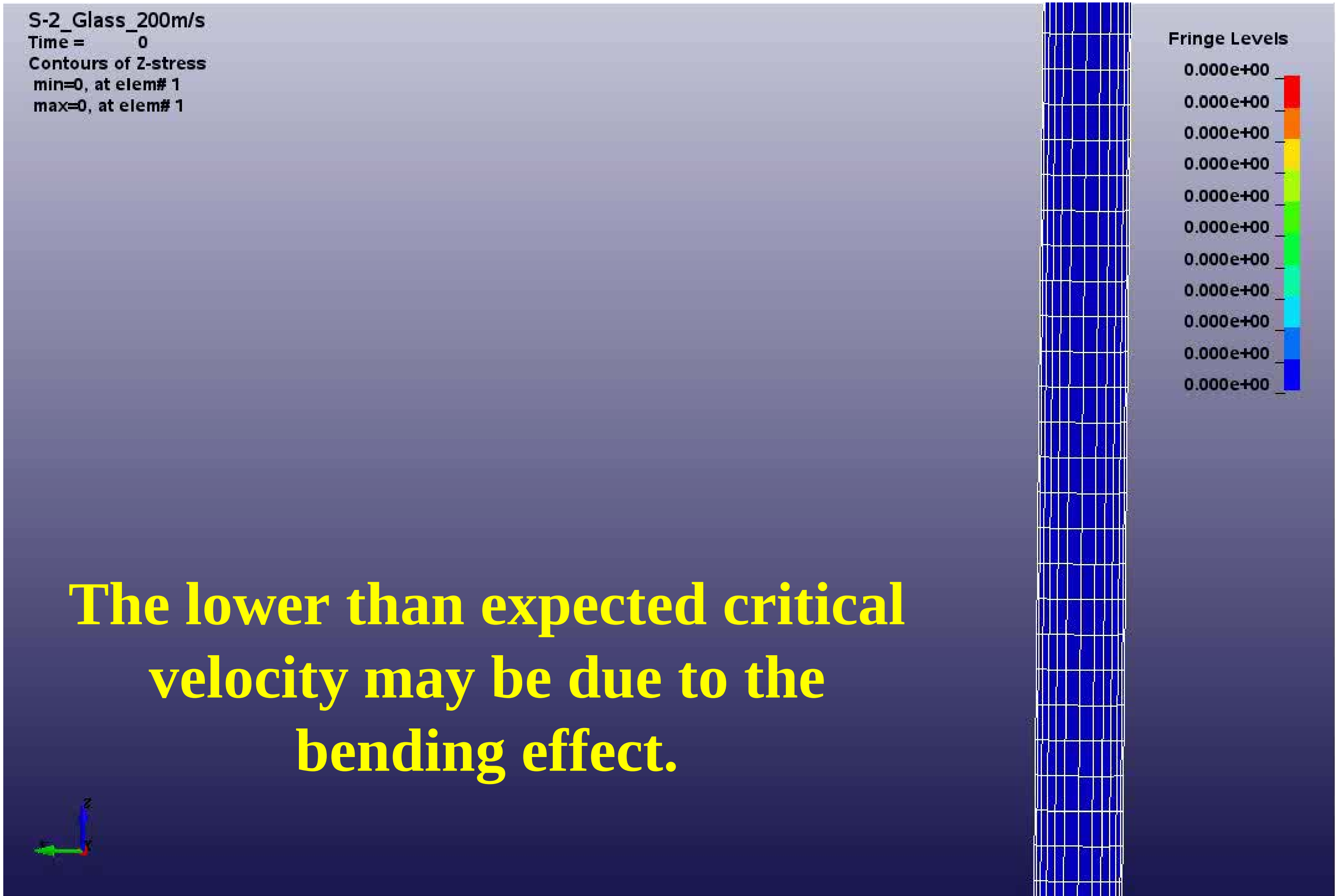
An Intriguing Result



- Scatter may be an artifact due to inconsistency in crimp when performing the test.
- The ballast decreases the scatter.
- But the results above the no crimp theoretical result should not be there!
- How come the transv. wave velocity can be larger than the prediction from theory?
- Why were we doing so well with polymeric fibers and not as well with S-2 glass?

Computer Simulations with LS-DYNA

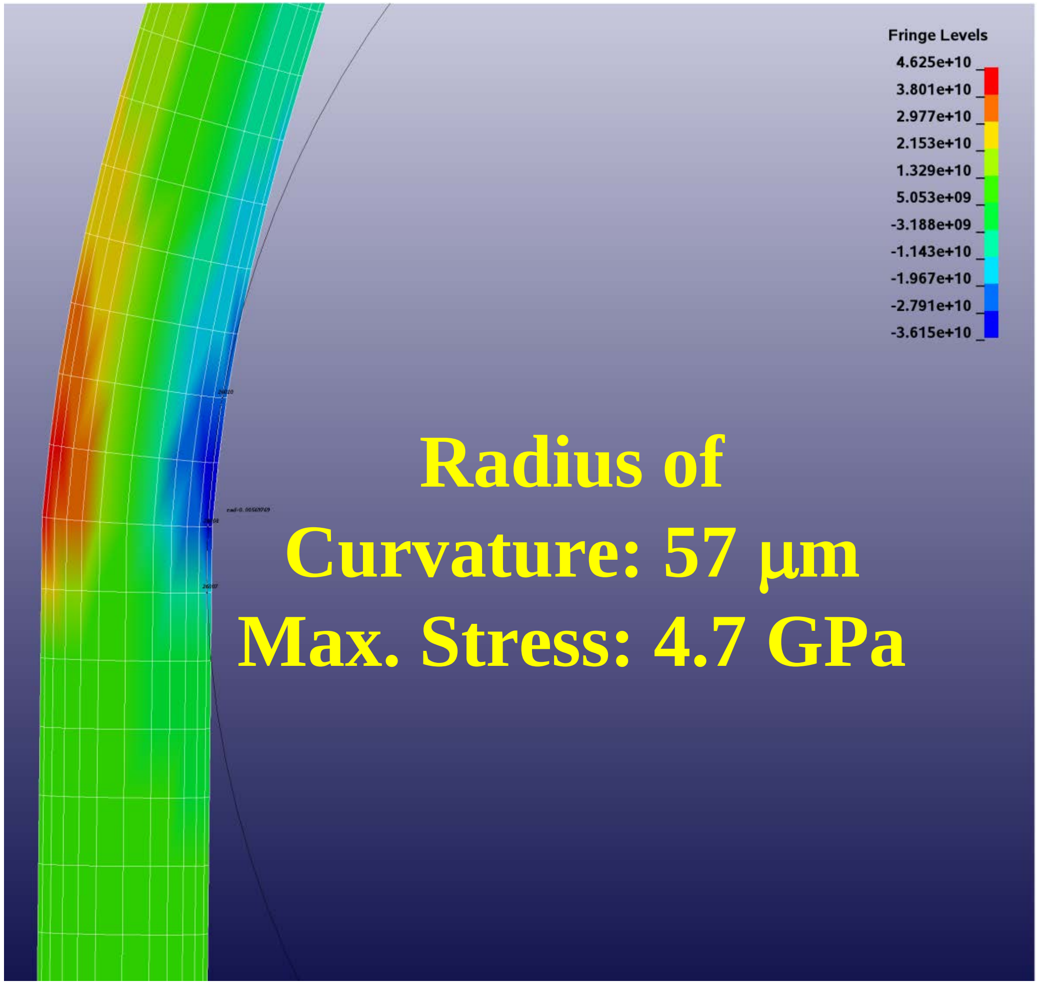
S-2 Glass 10 μm Fiber Impacted at 200 m/s (Boundary Condition)



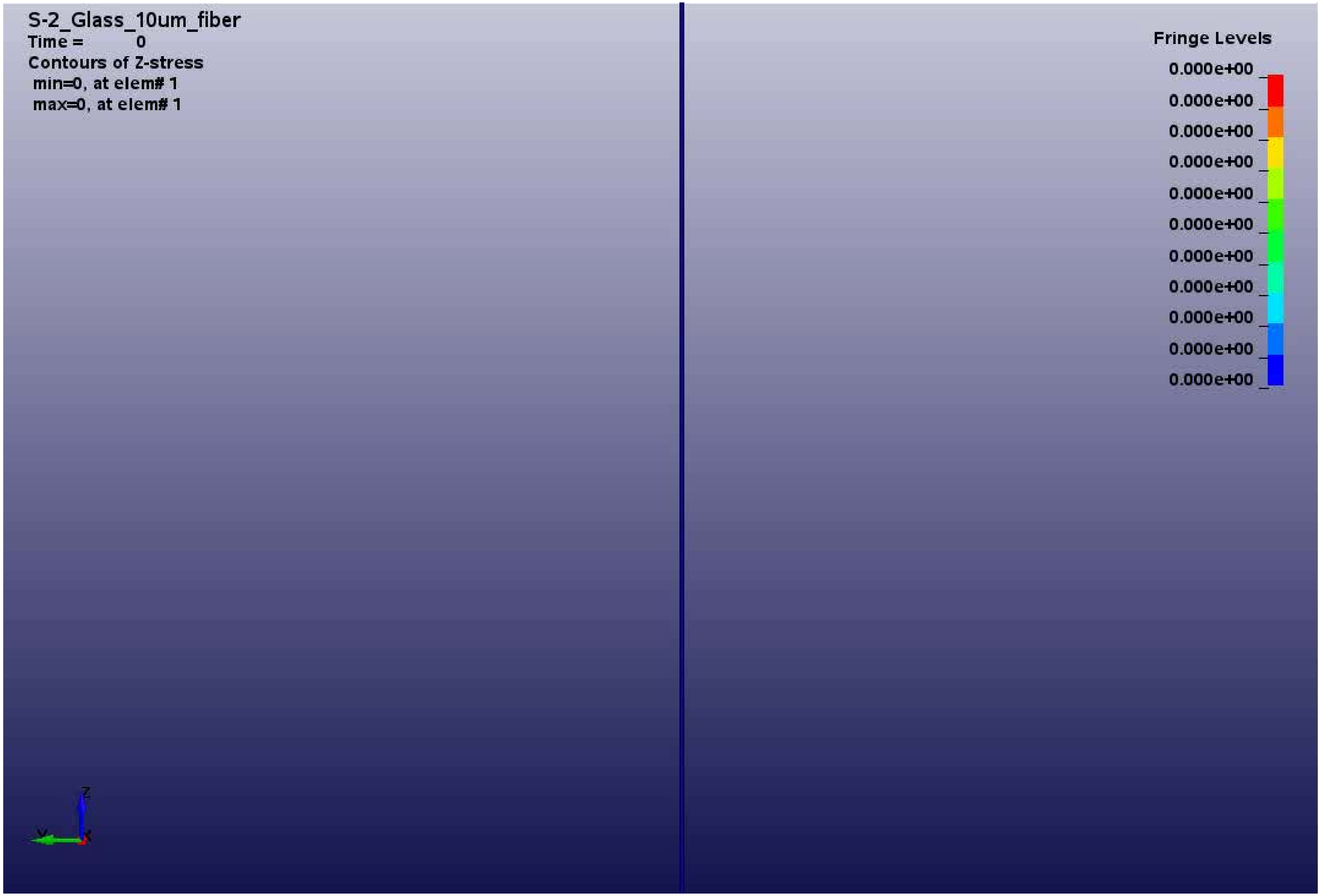
The lower than expected critical velocity may be due to the bending effect.

Boundary Condition at 200 m/s

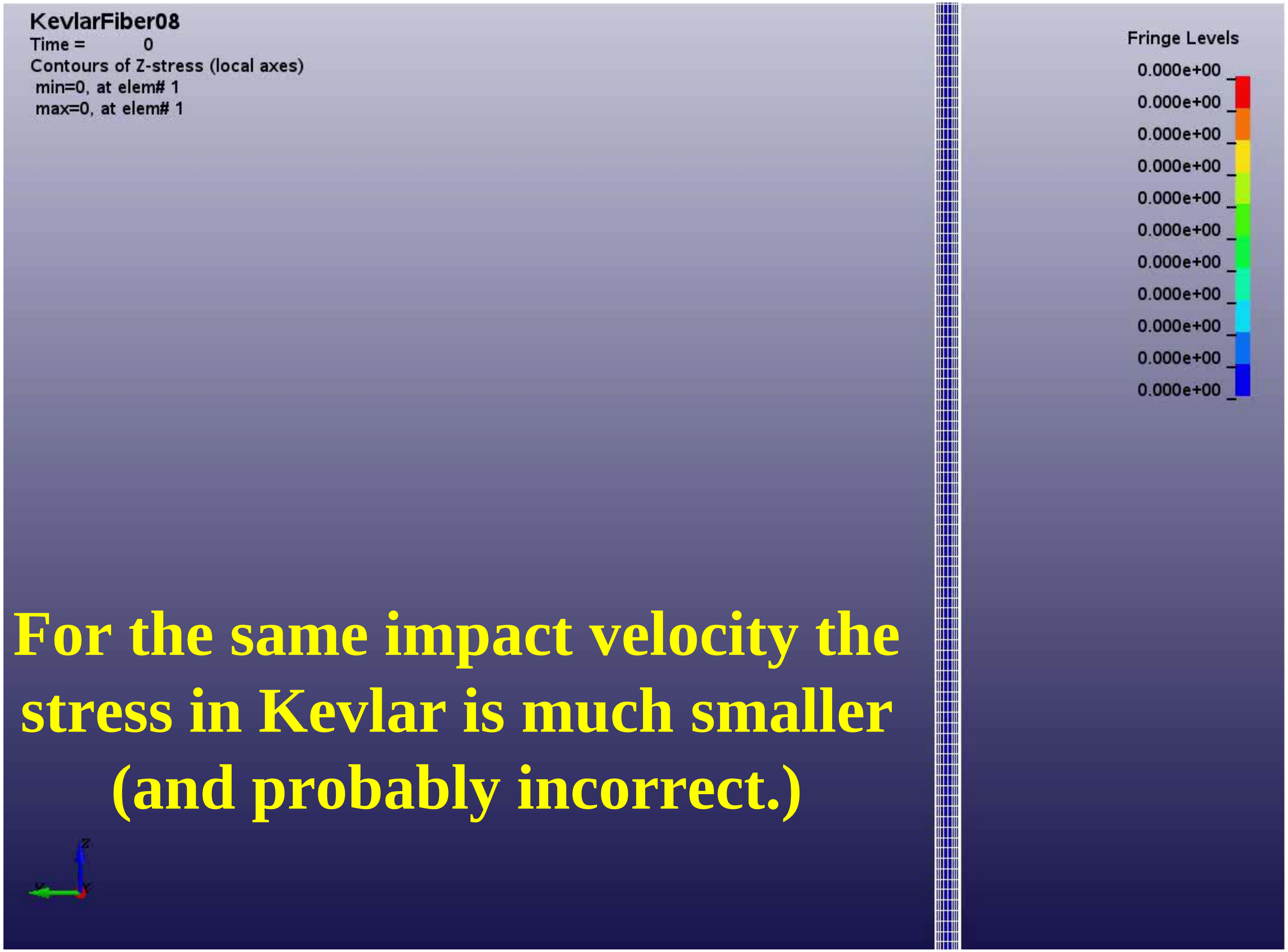
- This is a 10 μm diameter S2-glass fiber.
- A rough radius of curvature for failure of S-2 glass is 100 μm.
- Polymeric fibers microstructure is very different and can withstand much sharper radius of curvature.



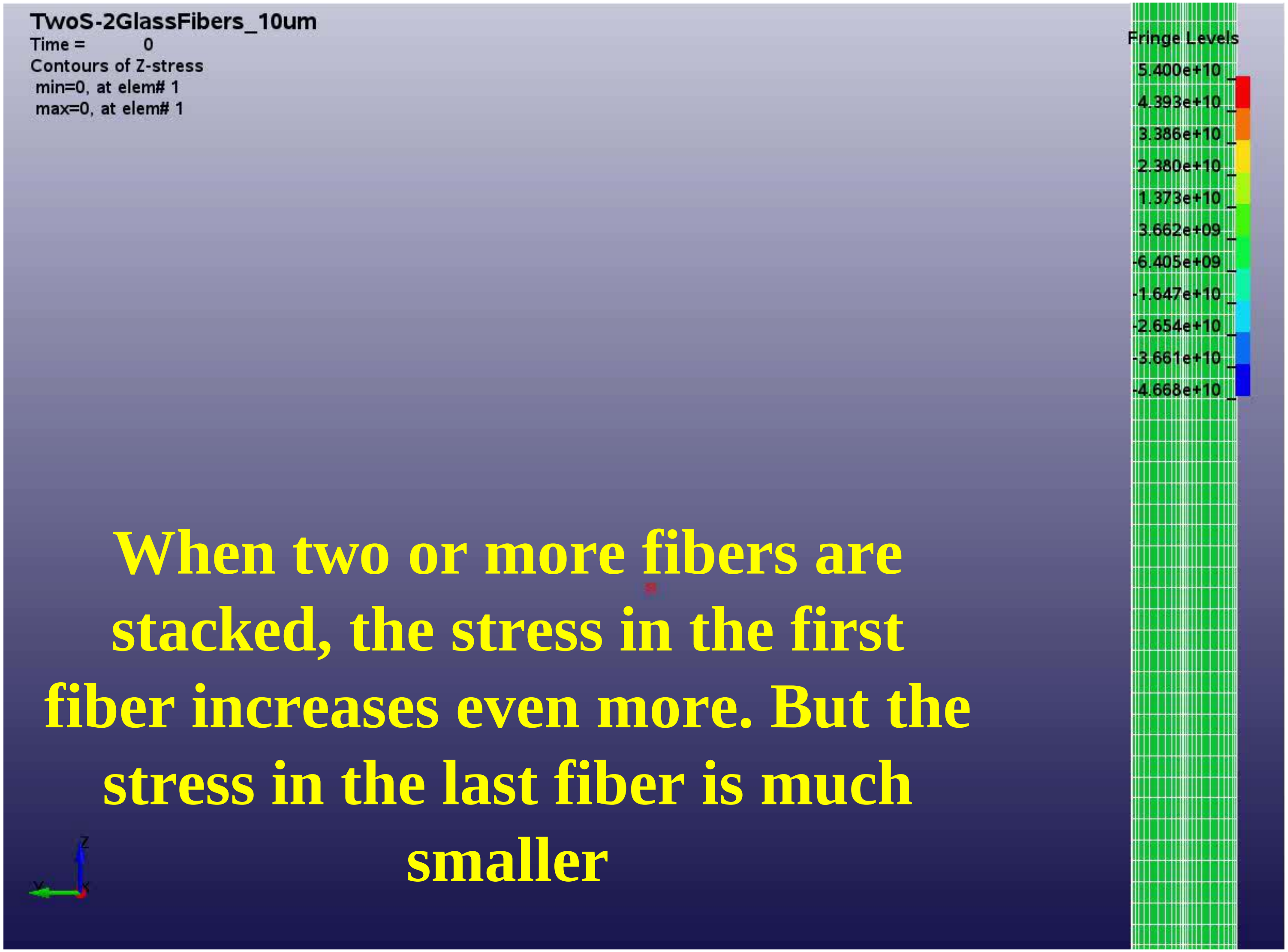
Stress in S-2 glass Fiber, 200 m/s (isotropic)



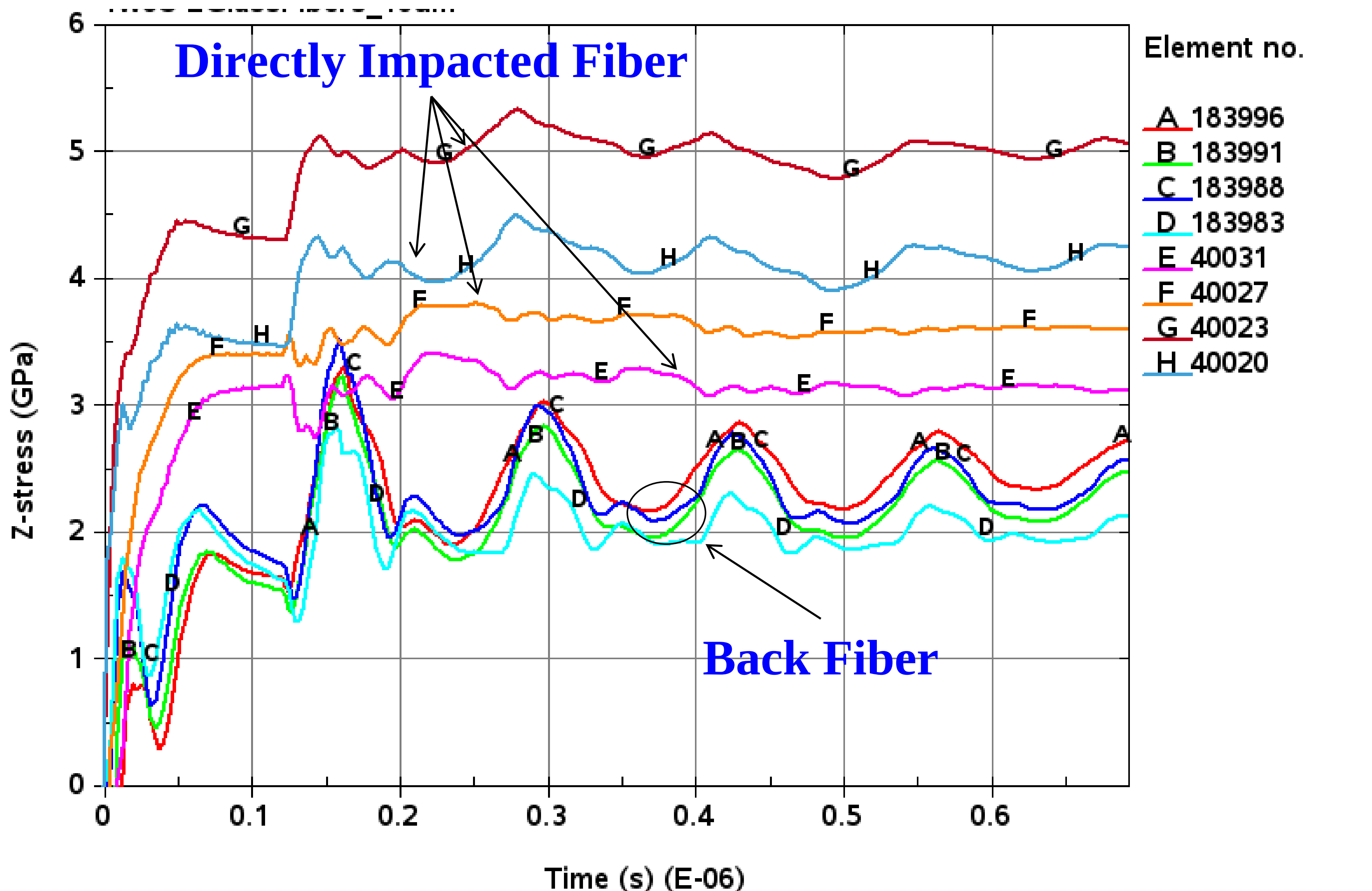
Stress in Kevlar Fiber, 200 m/s (orthotropic)



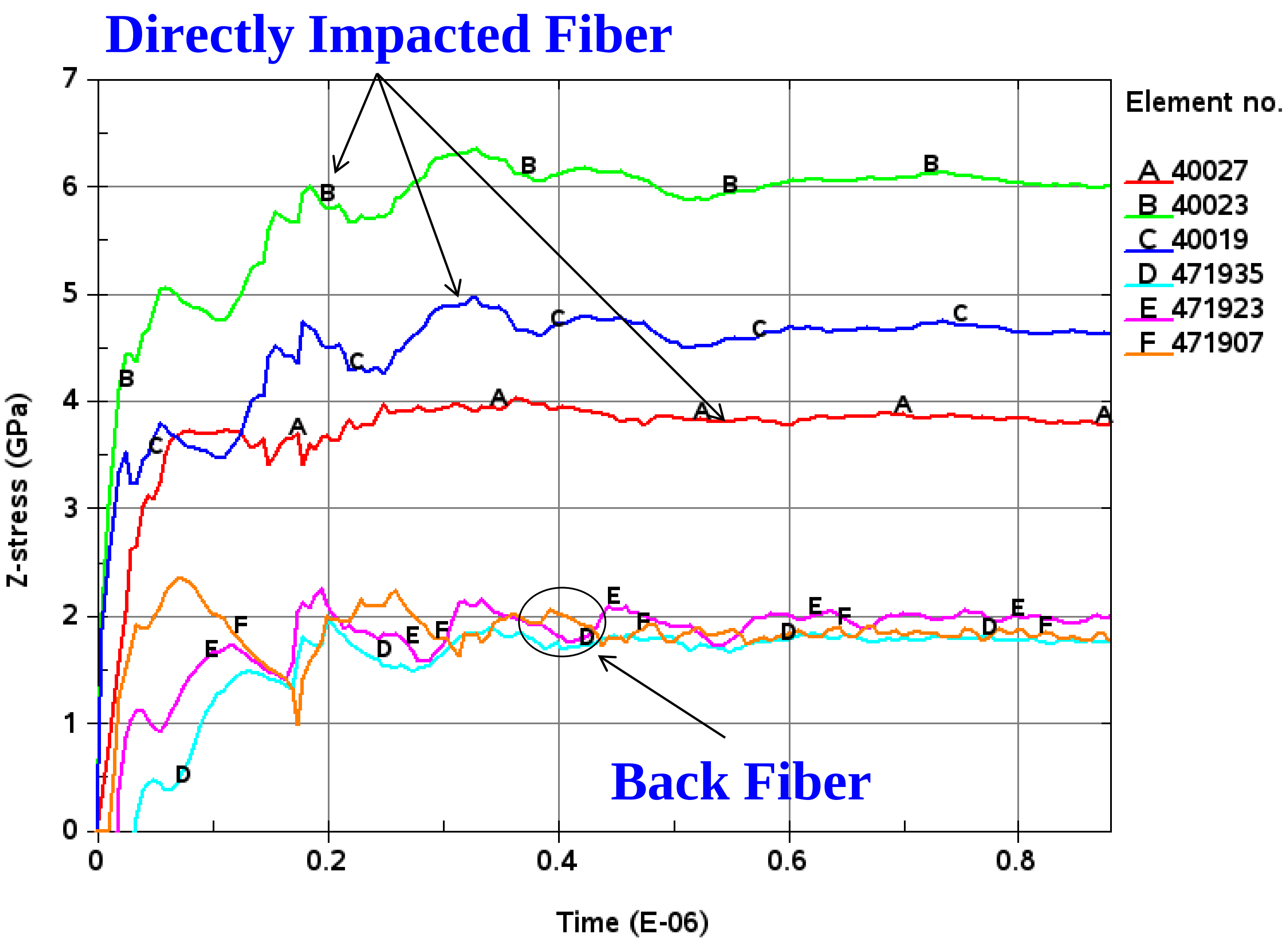
Two Fibers of S-2 glass Impacted at 200 m/s



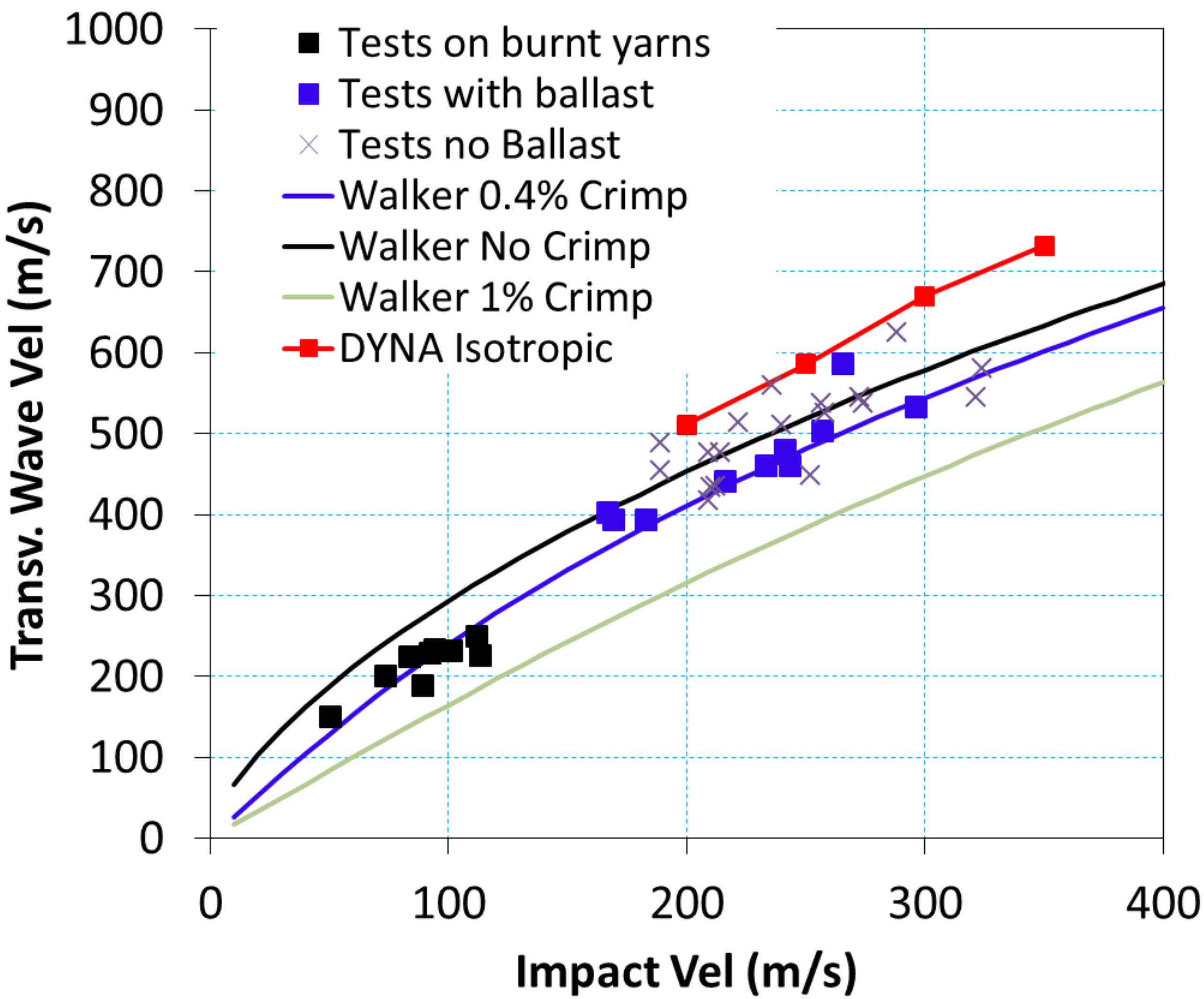
Stress on the Two Fibers



Four Fibers Impacted

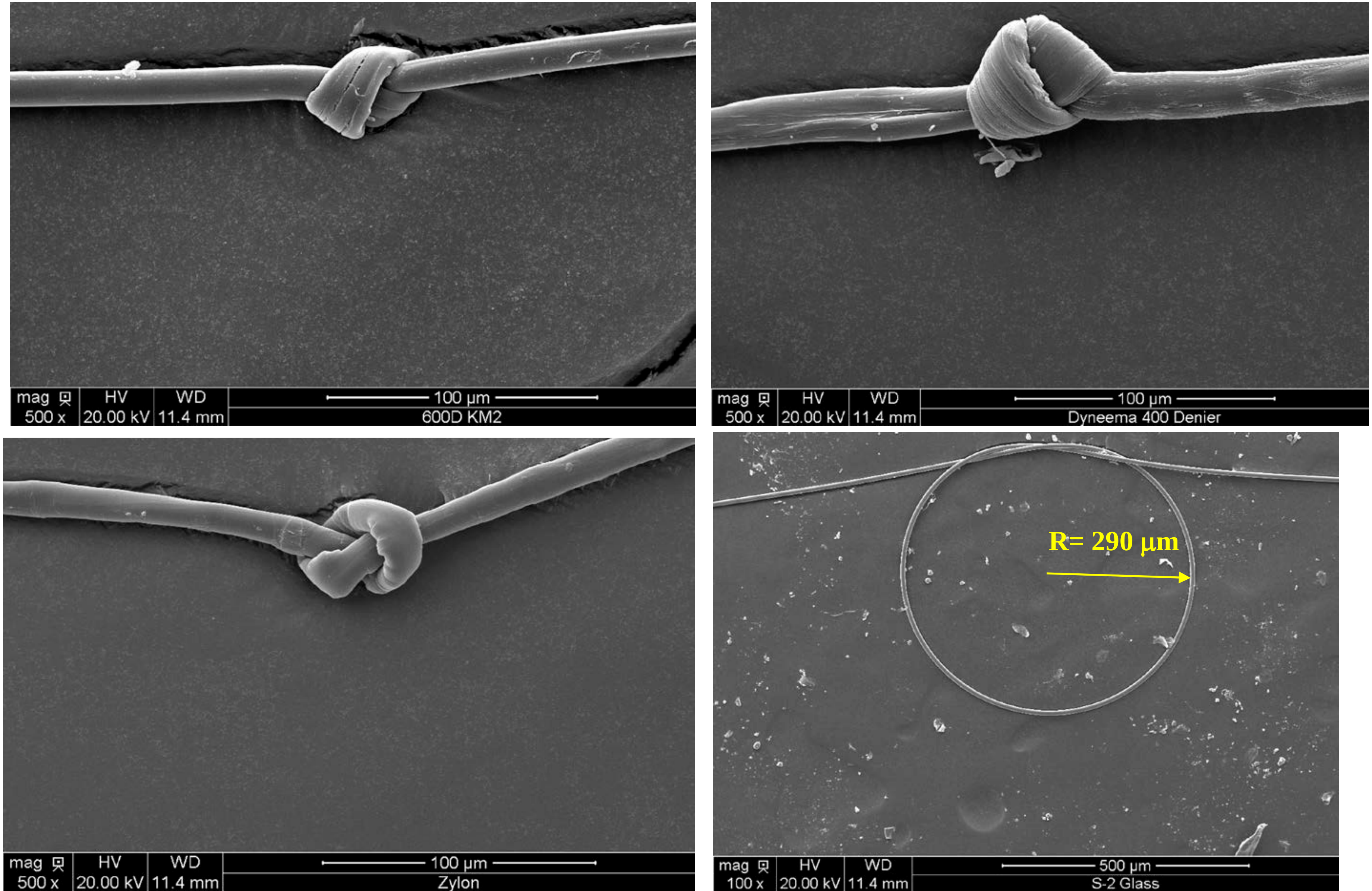


Transverse Wave Velocity from LS-DYNA (with Bending Stiffness)

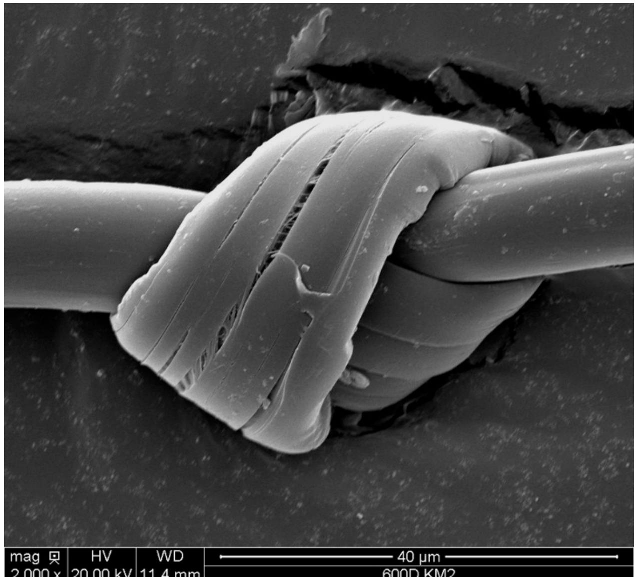


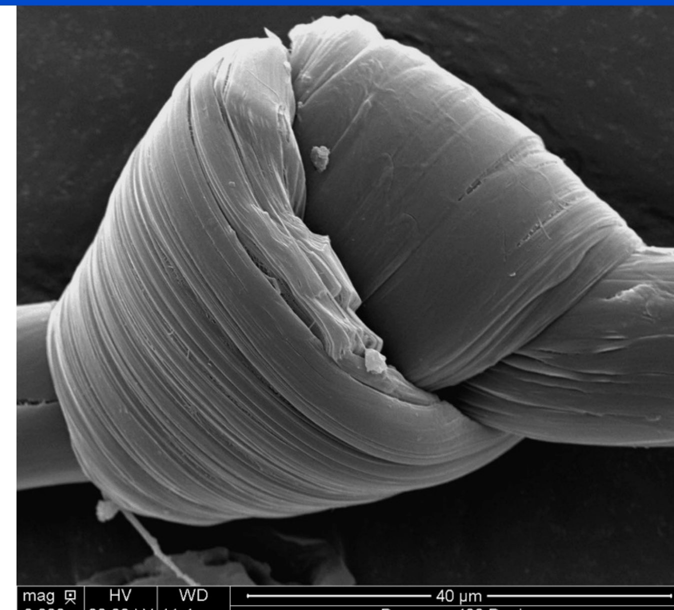
Comments on Failure Mechanisms for Polymer and Glass Fibers

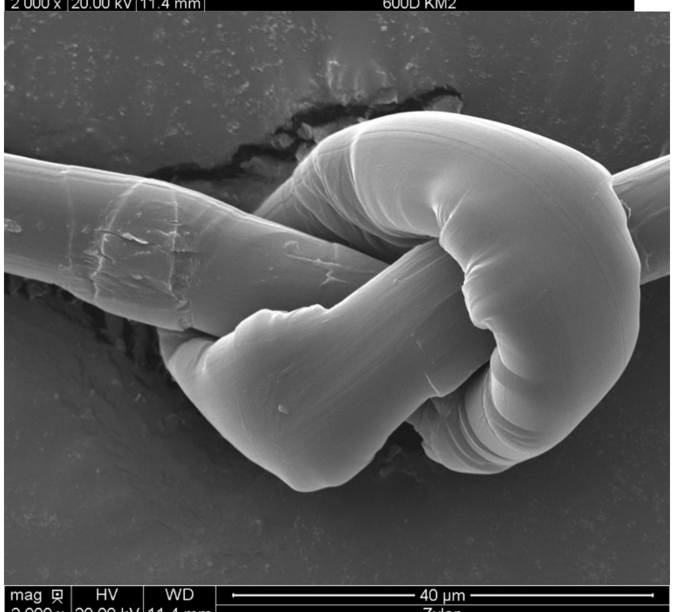
Knots in Kevlar, Dyneema, and PBO

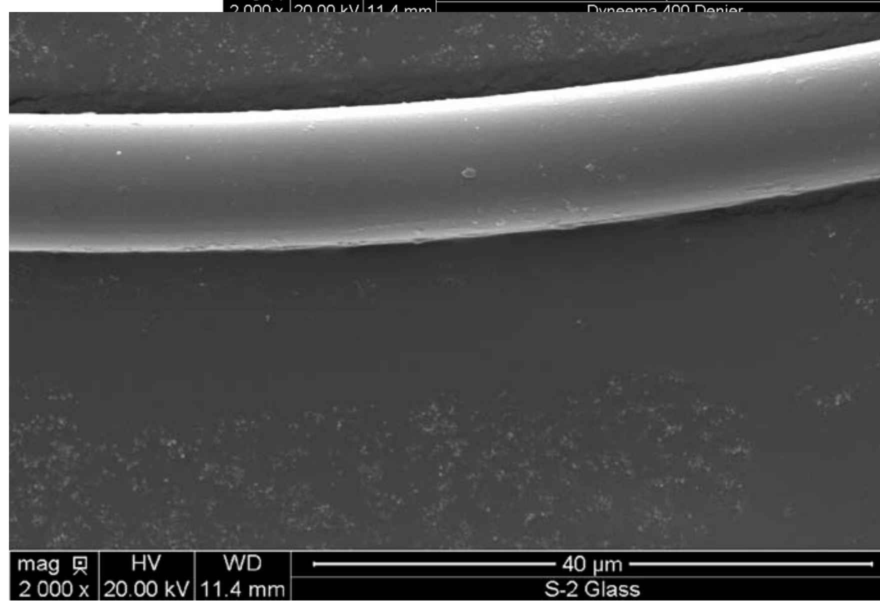


Knots in Kevlar, Dyneema, and PBO

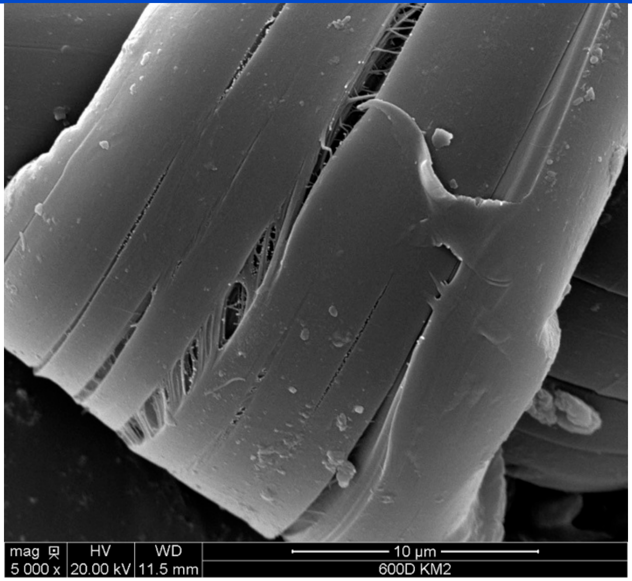


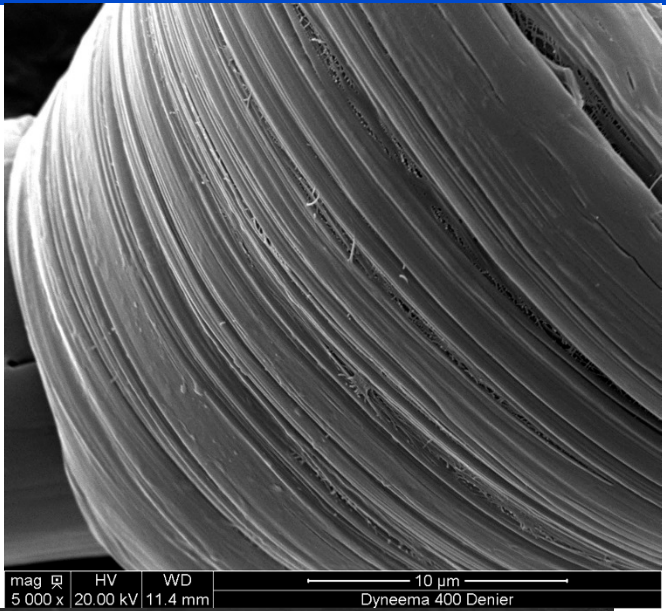


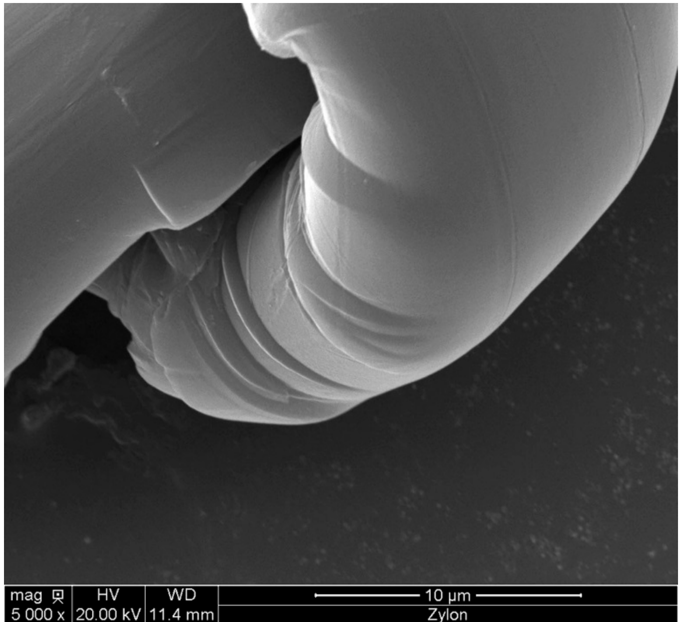


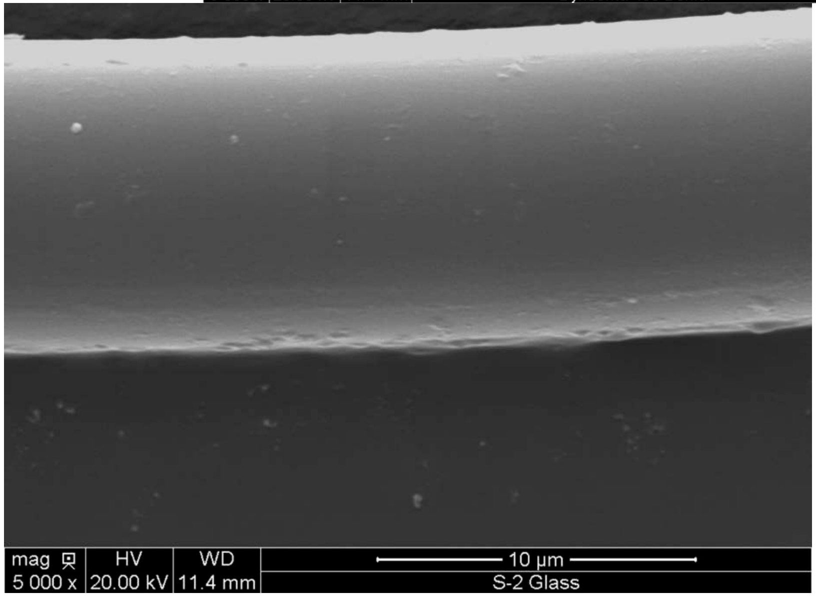


Knots in Kevlar, Dyneema, and PBO









Comments on Failure Modes of Fibers

- Polymeric fibers under severe bending like a knot seem to buckle the microfibrils.
- There is no evidence of failure in the micrographs, i.e. if the knot is untied the strength of the fiber may be kept.
- These fibers are composed of a bundle of microfibrils and are probably very insensitive to bending.
- On the other hand S-2 glass, an isotropic fiber (9 μm diameter) with a "solid" core, is probably very sensitive to bending. The tensile stresses on the external side of the knot make it break for a radius of ~100 μm.
- Simulations show that, with an impact boundary condition of 200 m/s the radius is smaller than the critical radius.

Conclusions

- The results of transverse ballistic impact on S-2 glass yarns have been reported.
- Two interesting effects were observed:
  - The transverse wave velocity in the yarns is larger than what Smith and Walker theories predict.
  - The critical velocity is much smaller than expected, with a large transition region between 200 and 350 m/s.
- The transverse impact theory was modified to understand the effect of crimp on the transverse wave velocity. Numerical simulations confirmed the validity of the model for fibers without bending stiffness.

Conclusions (cont'd)

- The theory and numerical simulations show that, without bending stiffness, the transverse wave velocity is underpredicted.
- When bending stiffness is added, the transverse wave velocity predicted by the simulations bounds the experiments.
- The low critical velocity has been explained in terms of stresses caused by bending for S-2 glass.
- Bending stresses are not that large in orthotropic fibers. Finding bending stresses in a fiber made of microfibrils is probably a very difficult task.
- Stacking fibers of S-2 glass reduces the bending stress on the fibers that are not directly impacted. The reason is that the curvature they see is larger. This may explain the large transition region for the critical velocity.

Acknowledgments

- Rick Rickert and Timothy Talladay for supporting the work through a contract with TARDEC.
- Uli Heisserer and Harm van der Werff for discussions on the microfibril structure of Dyneema.